Systems-Theoretic Early Concept Analysis (and Development)

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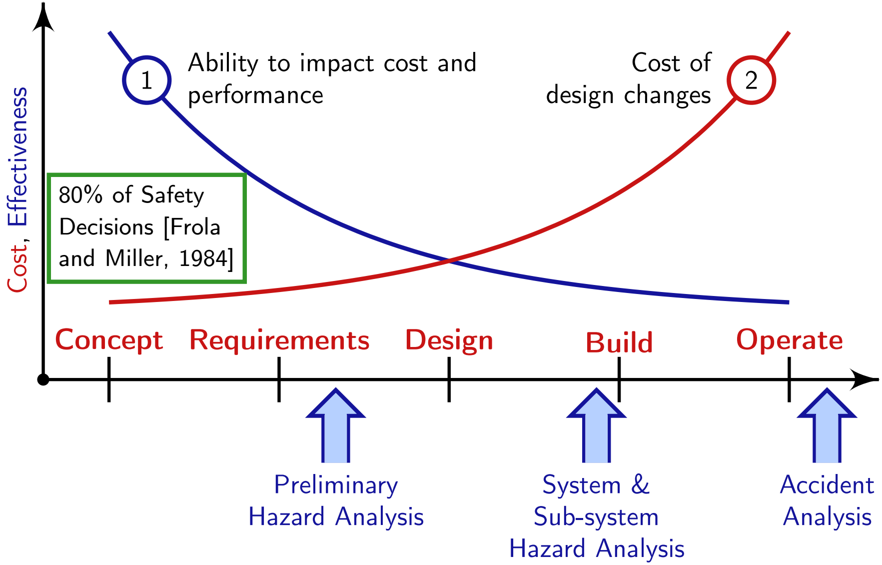
4th STAMP Workshop

Systems Engineering Research Lab

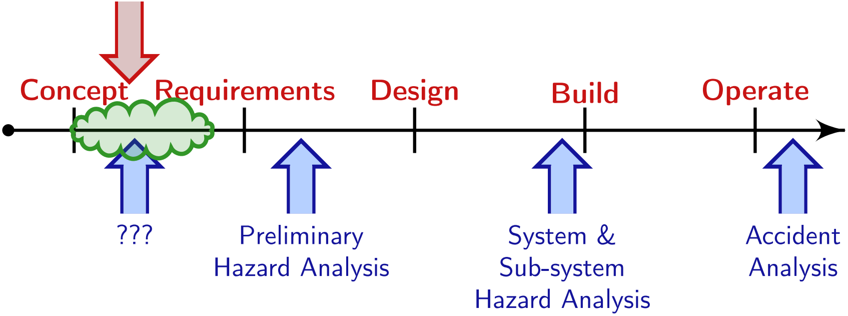
Motivation



Cost, Effectiveness
1
Ability to impact cost and performance
Cost of design changes
2
80% of Safety Decisions [Frola and Miller, 1984]
Concept
Requirements
Design
Build
Operate
Preliminary Hazard Analysis
System & Sub-system Hazard Analysis
Accident Analysis

General Challenges

- limited design information
- no specification
- informal documentation
- concept of operations ≡ “ConOps”



Goals

1. use rigorous, systematic tools for identifying hazardous scenarios and undocumented assumptions

2. supplement existing (early) SE activities such as requirements definition, architectural and design studies

Especially when tradespace includes: ***human*** operation, ***automation*** or decision support tools, and the ***coordination*** of decision making agents

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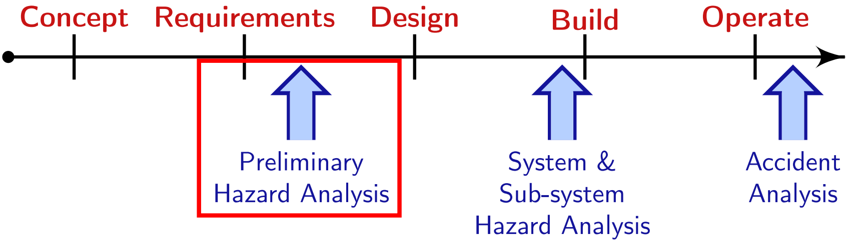
Current State of the Art



Current State of the Art

Preliminary Hazard Analysis

PROGRAM: ______________				DATE: ______		
ENGINEER: ______________				PAGE: ______		
ITEM	HAZARD COND	CAUSE	EFFECTS	RAC	ASSESS-MENTS	RECOMM-ENDATIONS
Assigned number	List the nature of the condition	Describe what is causing the stated condition to exist	If allowed to go uncorrected, what will be the effect or effects of the hazardous condition	Hazard Level assign-ment	Probability, possibility of occurrence: -Likelihood -Exposure -Magnitude	Recommended actions to eliminate or control the hazard

[Vincoli, 2005]

Limitations of PHA

PHA tends to identify the following hazard causes:

Causes	Causes	Causes
Equipment Failure	Design error, coding error, insufficient software testing, software operating system problem	Human error

[JPDO, 2012]

This is true:

ALL accidents are caused by hardware failure, software flaws, or human error

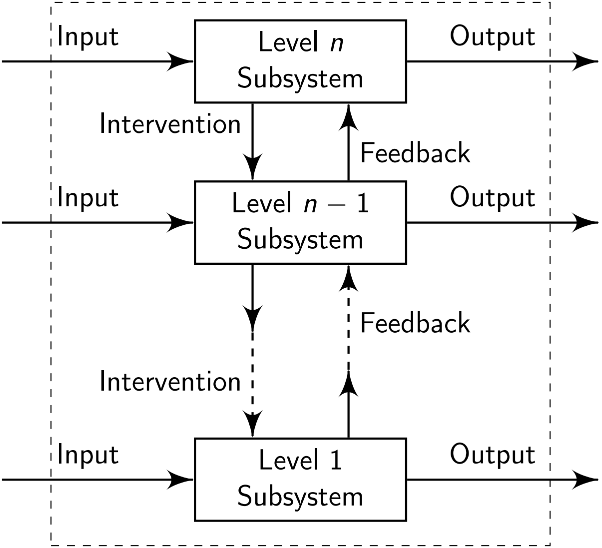
But is the information coming from PHA useful for systems engineering?

Emergence

Organized complexity as a hierarchy of levels, "each more complex than the one below, a level being characterized by emergent properties which do not exist at the lower level" [Checkland, 1999]

[Business Korea, 2014]

Hierarchy



[Mesarovic, 1970]

Process Control

Four conditions are required for process control:

1. *Goal* condition: the controller must have a goal or goals
2. *Action* condition: the controller must be able to affect the state of the system, typically by means of an actuator or actuators
3. *Model* condition: the controller must contain a model of the system
4. *Observability* condition: the controller must be able to ascertain the state of the system, typically by feedback from a sensor

[Ashby, 1957]

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Safety $\Rightarrow$ Control Problem

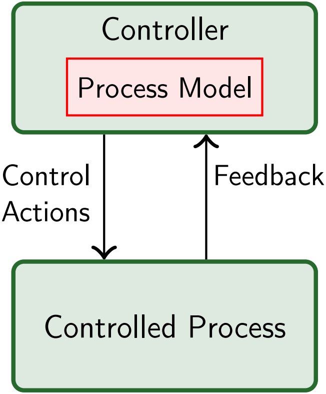
Systems-Theoretic Accident Model and Process

STAMP

- Accidents are more than a chain of events, they involve complex dynamic processes
- Treat accidents as a control problem, not a failure problem
- Prevent accidents by enforcing constraints on component behavior and interactions

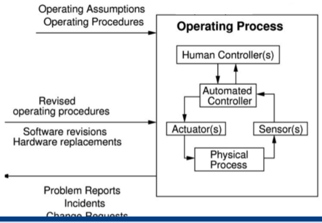
STAMP

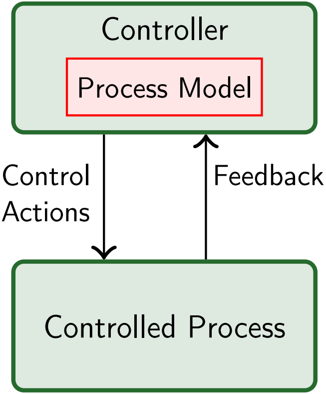
- Controllers use a **process model** to determine control actions
- Accidents often occur when the process model is incorrect
- Four types of unsafe control actions:
  1. **Not providing** the control action causes the hazard
  2. **Providing** the control action causes the hazard
  3. The **timing** or **sequencing** of control actions leads to the hazard
  4. The **duration** of a continuous control action, i.e., too short or too long, leads to the hazard.



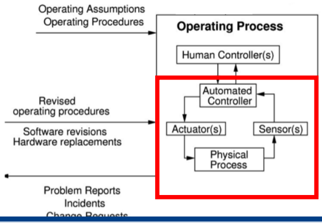
Better model of both software and human behavior
Explains software errors, human errors, interaction accidents,...

STAMP


Operating Assumptions
Operating Procedures
Operating Process
Human Controller(s)
Automated Controller
Actuator(s)
Sensor(s)
Physical Process
Revised operating procedures
Software revisions
Hardware replacements
Problem Reports
Incidents


Controller
Process Model
Control Actions
Feedback
Controlled Process

STAMP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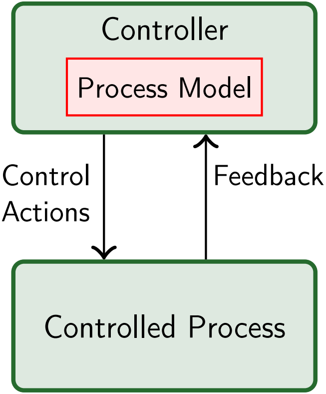
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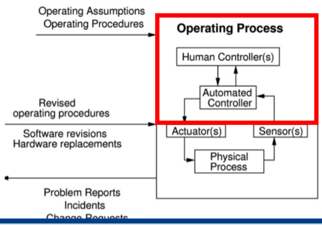
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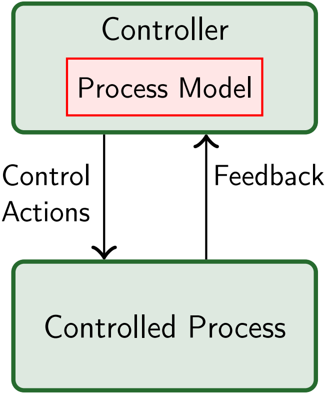
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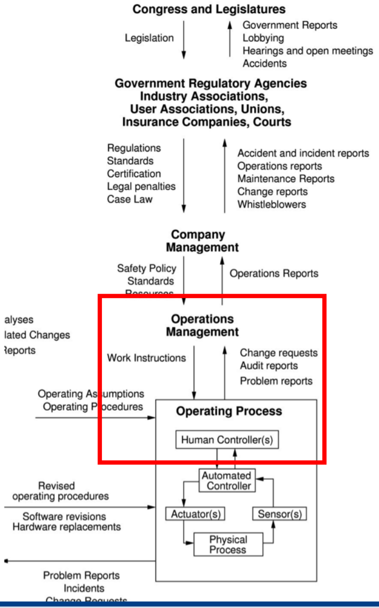
Congress and Legislatures
Legislation
Government Reports
Lobbying
Hearings and open meetings
Accidents
Government Regulatory Agencies
Industry Associations,
User Associations, Unions,
Insurance Companies, Courts
Regulations
Standards
Certification
Legal penalties
Case Law
Accident and incident reports
Operations reports
Maintenance Reports
Change reports
Whistleblowers
Company
Management
Safety Policy
Standards
Operations Reports
Operations
Management
Work Instructions
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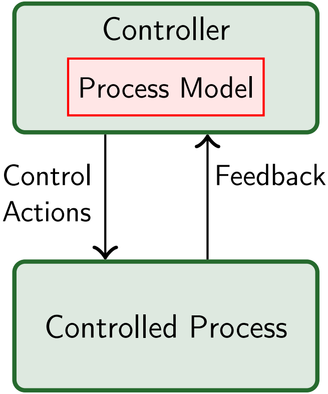
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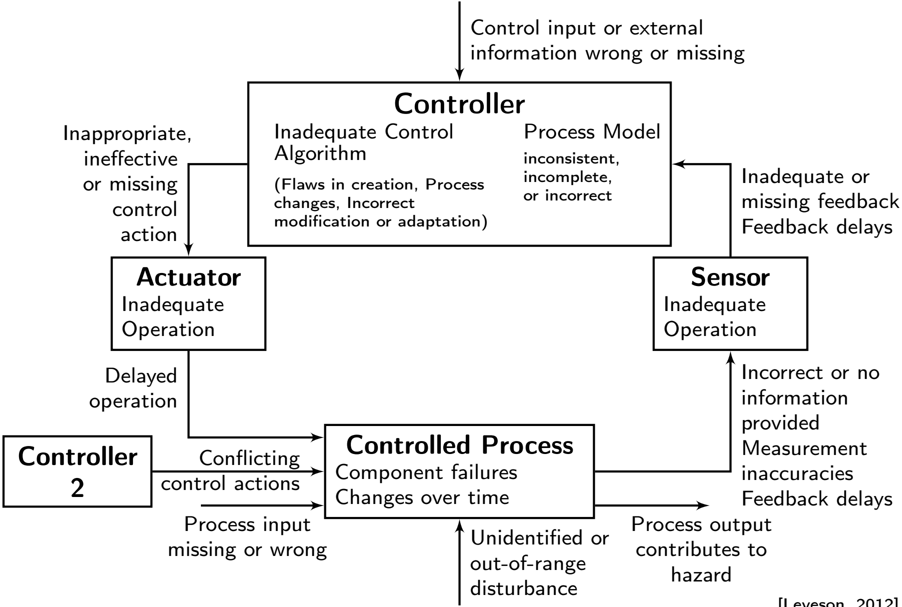
Unsafe Control Actions

Control Action	Not Providing Causes Hazard	Providing Causes Hazard	Wrong Timing/Order Causes Hazard	Stopped Too Soon/Applied Too Long
Execute ITP		ITP executed when not approved ITP executed when ITP criteria are not satisfied ITP executed with incorrect climb rate, final altitude, etc	ITP executed too soon before approval ITP executed too late	
Abnormal Termination of ITP	FC continues with maneuver in dangerous situation	FC aborts unnecessarily FC does not follow regional procedures while aborting		

Control Flaws



[Leveson, 2012]

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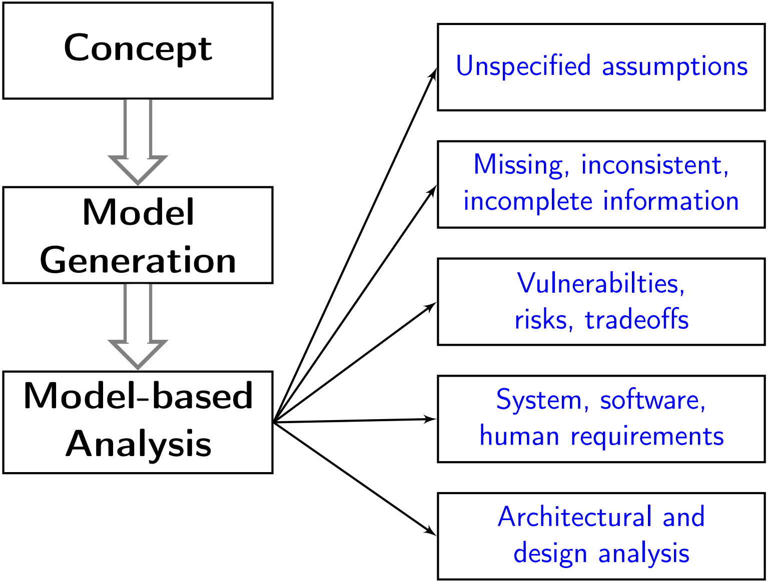
Approach

Systems-theoretic Early Concept Analysis—STECA

Approach


Concept
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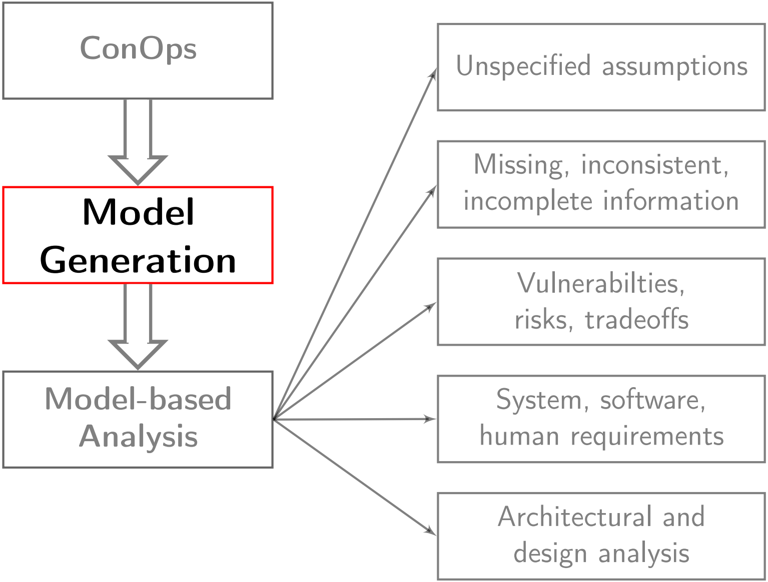
Model-based Analysis
Unspecified assumptions
Missing, inconsistent, incomplete information
Vulnerabilties, risks, tradeoffs
System, software, human requirements
Architectural and design analysis

Control Elements



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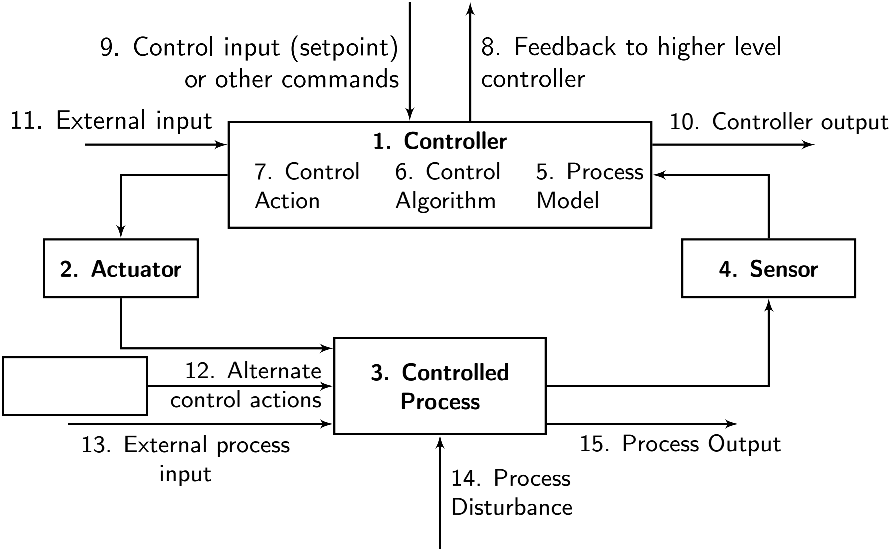


Roles in Control Loop

What kinds of things can an "entity" do within a control structure, and more particularly within a control loop?

Roles in Control Loop

What kinds of things can an "entity" do within a control structure, and more particularly within a control loop?

Controller

- Enforces safety constraints
- Creates, generates, or modifies control actions based on algorithm or procedure and perceived model of system
- Processes inputs from sensors to form and update process model
- Processes inputs from external sources to form and update process model
- Transmits instructions or status to other controllers

Roles in Control Loop

What kinds of things can an "entity" do within a control structure, and more particularly within a control loop?

Actuator

- Translates controller-generated action into process-specific instruction, force, heat, etc

Roles in Control Loop

What kinds of things can an "entity" do within a control structure, and more particularly within a control loop?

Controlled Process

- Interacts with environment via forces, heat transfer, chemical reactions, etc
- Translates higher level control actions into control actions directed at lower level processes

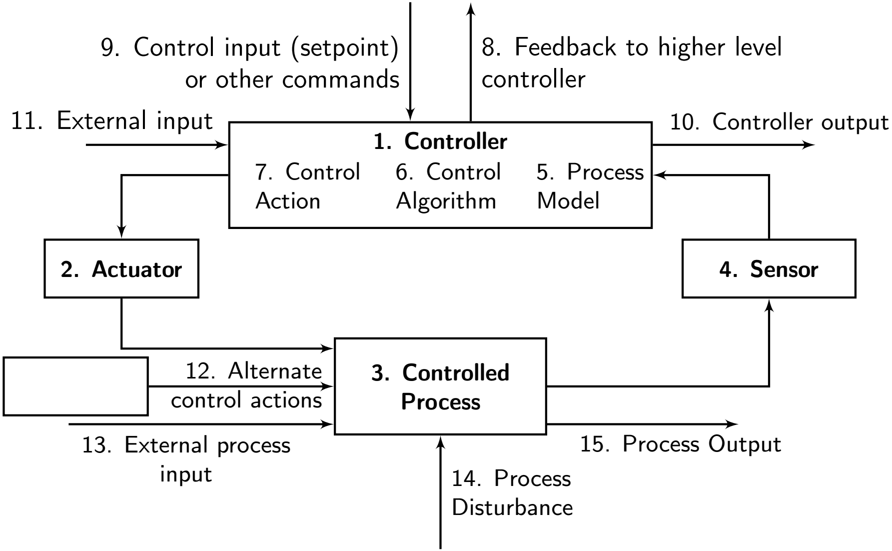
Roles in Control Loop

What kinds of things can an "entity" do within a control structure, and more particularly within a control loop?

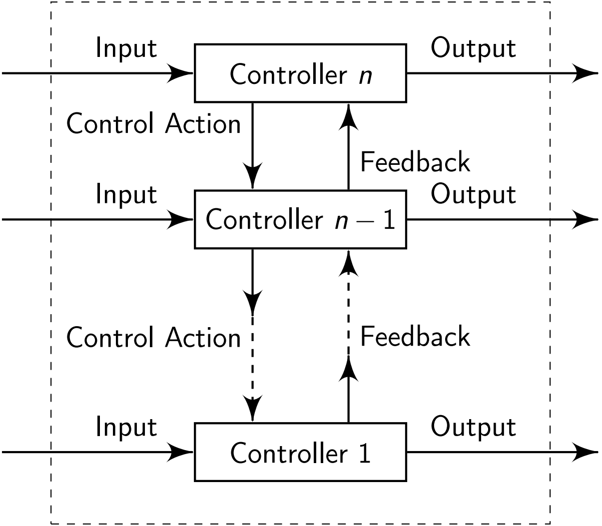
Sensor

- Transmits continuous dynamic state measurements to controller (i.e. measures the behavior of controlled process via continuous or semi-continuous [digital] data)
- Transmits binary or discretized state data to controller (i.e. measures behavior of process relative to thresholds; has algorithm built-in but no cntl authority)
- Sythesizes and integrates measurement data

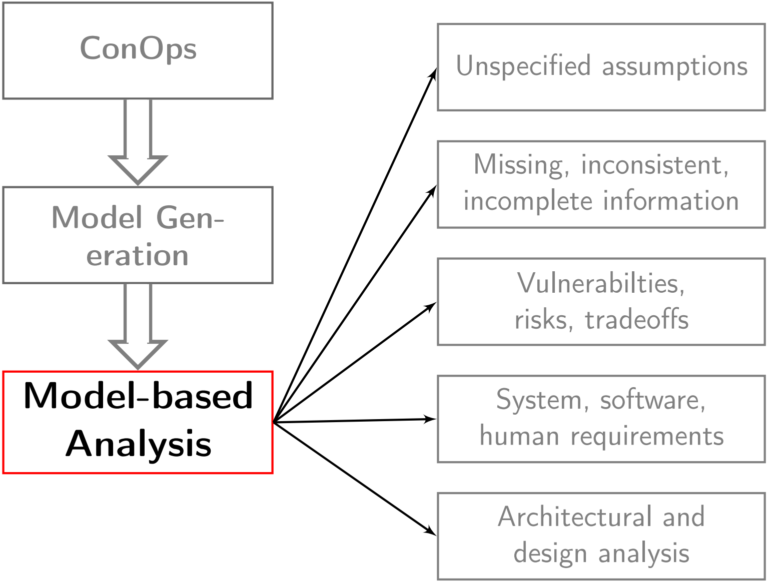
Individual Control Loop



Control Structure



Analysis



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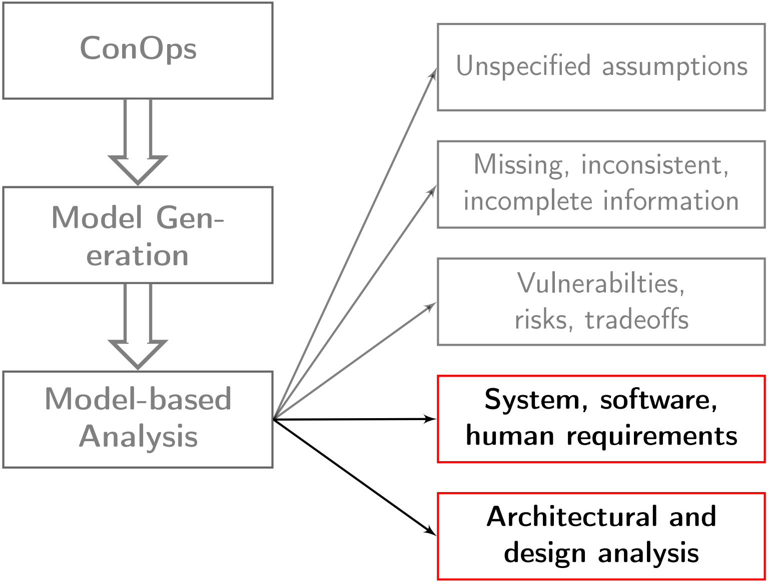
Analysis

"Completeness"

"Analyzing Safety-related Responsibilities"

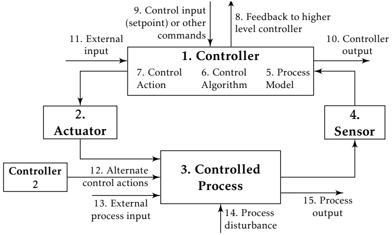
"Coordination & Consistency"

Early Systems Engineering

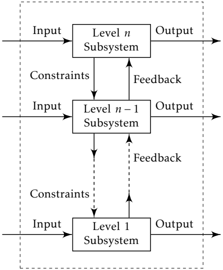


Early Systems Engineering

Constraints on control loop behavior



Model-Based Analysis



Change the control structure

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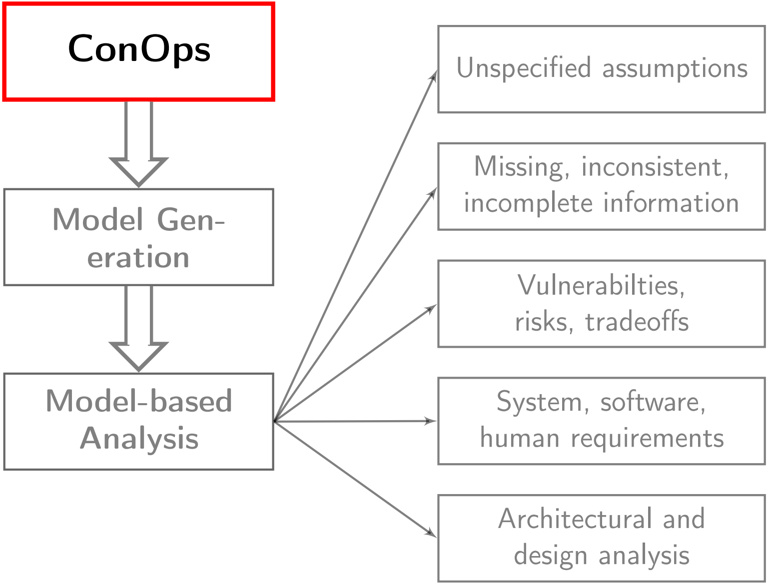
Application—TBO



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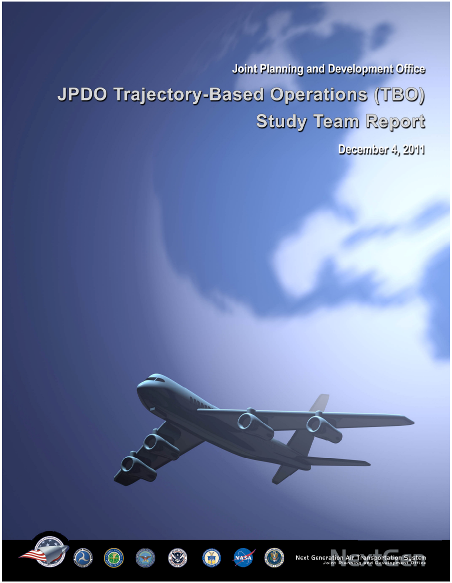

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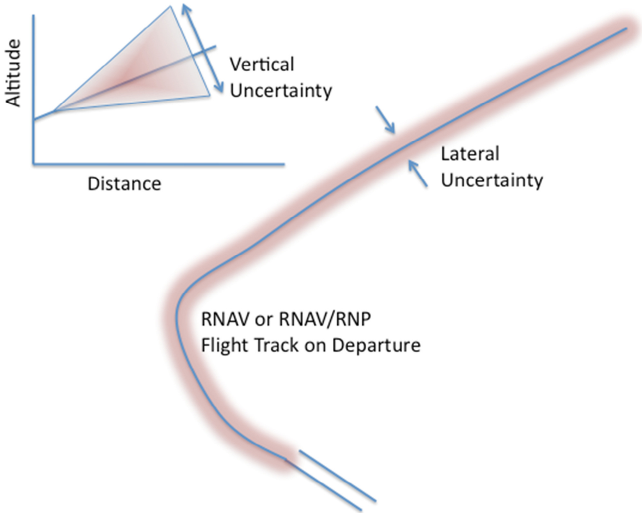
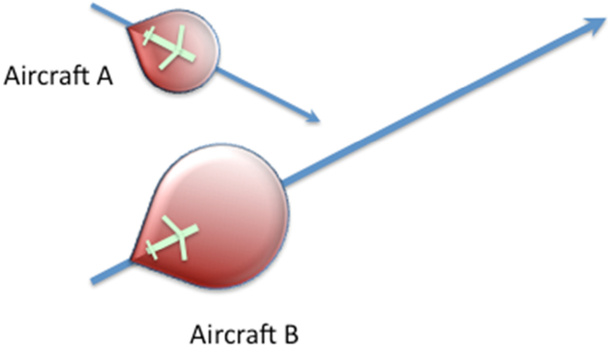


[JPDO, 2011]

Application—TBO



[JPDO, 2011]

System-Level Hazards

[H-1] Aircraft violate minimum separation (LOS or loss of separation, NMAC or Near midair collision)

[H-2] Aircraft enters uncontrolled state

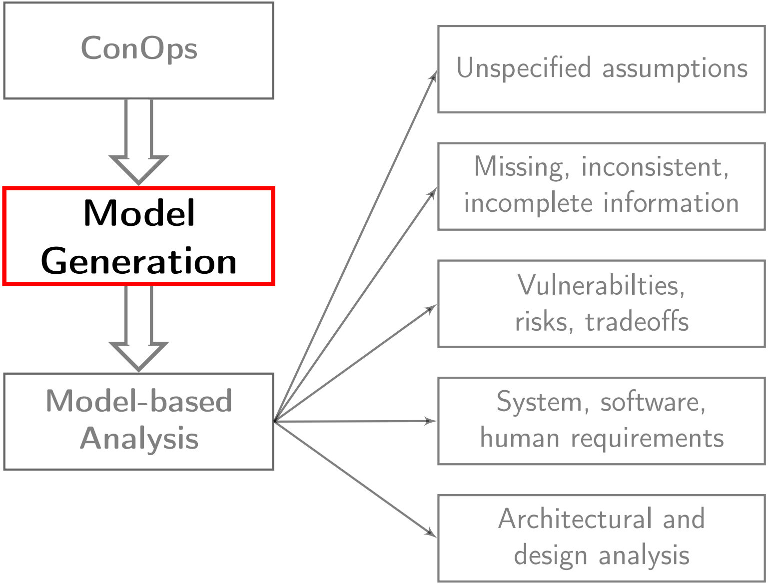
[H-3] Aircraft performs controlled maneuver into ground (CFIT, controlled flight into terrain)

[SC-1] Aircraft must remain at least TBD nautical miles apart en route* ↑[H-1]

[SC-2] Aircraft position, velocity must remain within airframe manufacturer defined flight envelope ↑[H-2]

[SC-3] Aircraft must maintain positive clearance with all terrain (This constraint does not include runways and taxiways) ↑[H-3]

Identify Control Concepts



Identify Control Concepts

TBO conformance is monitored both in the aircraft and on the ground against the agreed-upon 4DT. In the air, this monitoring (and alerting) includes lateral deviations based on RNP..., longitudinal ..., vertical..., and time from the FMS or other "time to go" aids. [JPDO, 2011]

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Subject
Role
Behavior Type
Context

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Subject	Conformance monitoring, Air automation
Role	Sensor
Behavior Type	Transmits binary or discretized state data to controller (i.e. measures behavior of process relative to thresholds; has algorithm built-in but no cntl authority)
	Sythesizes and integrates measurement data
Context	This is a decision support tool that contains algorithms to synthesize information and provide alerting based on some criteria.

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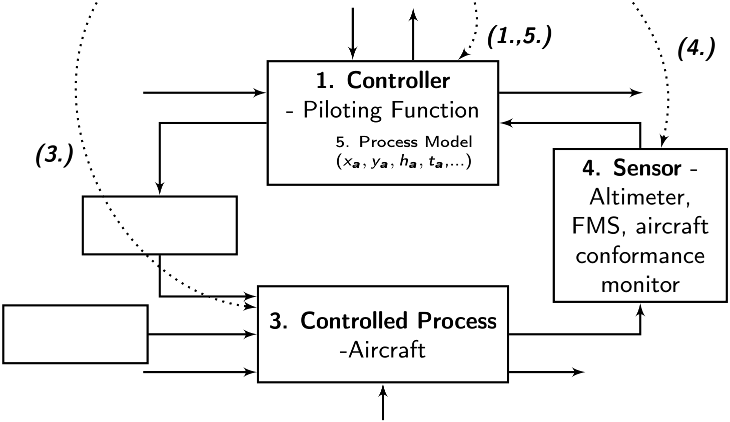

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1. Controller	Piloting function
2. Actuator	
3 Cntl'd Process	Aircraft
4. Sensor	Altimeter, FMS, Aircraft conformance monitor
5. Process Model	Intended latitude, longitude, altitude, time; Actual latitude, longitude, altitude, time
6. Cntl Algorithm	
7. Control Actions	
8. Controller Status	
9. Control Input	
10. Controller Output	
11. External Input	
12. Alt Controller	
13. Process Input	
14. Proc Disturbance	
15. Process Output	

Ground

Independent of the aircraft, the ANSP uses ADS-B position reporting for lateral and longitudinal progress, altitude reporting for vertical, and tools that measure the time progression for the flight track. Data link provides aircraft intent information. Combined, this position and timing information is then compared to a performance requirement for the airspace and the operation. ...precision needed...will vary based on the density of traffic and the nature of the operation. [JPDO, 2011]

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Role	Sensor
Behavior Type	Transmits binary or discretized state data to controller (i.e. measures behavior of process relative to thresholds; has algorithm built-in but no cntl authority)
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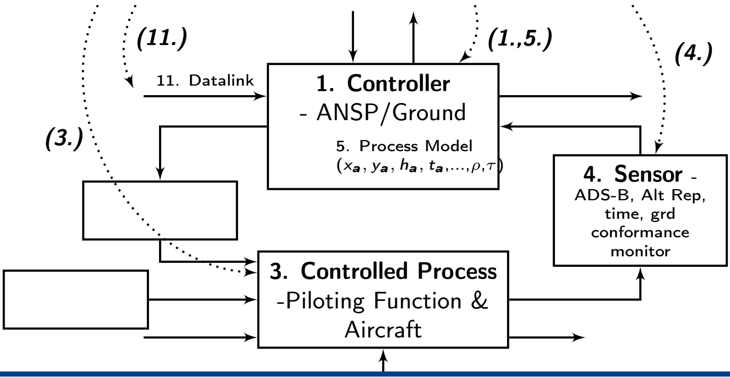
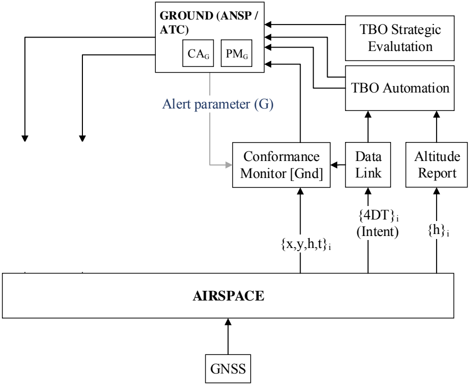


Conf Monitoring Control Loops

"Ground"



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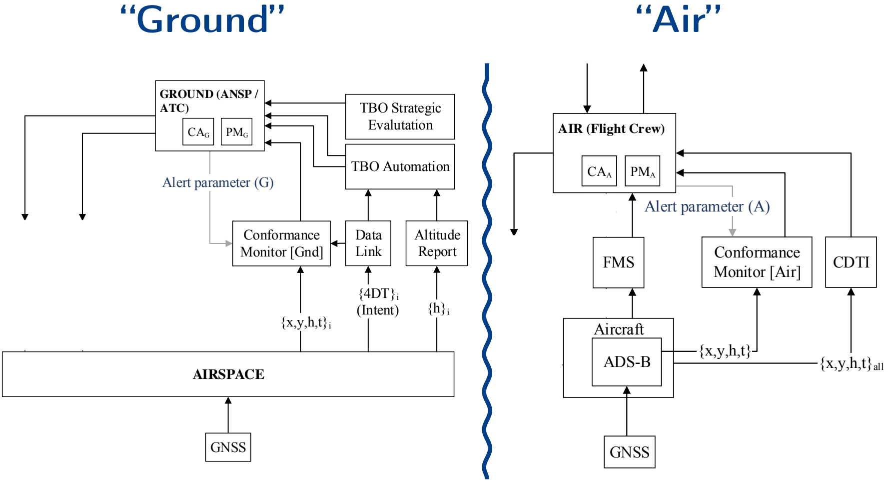
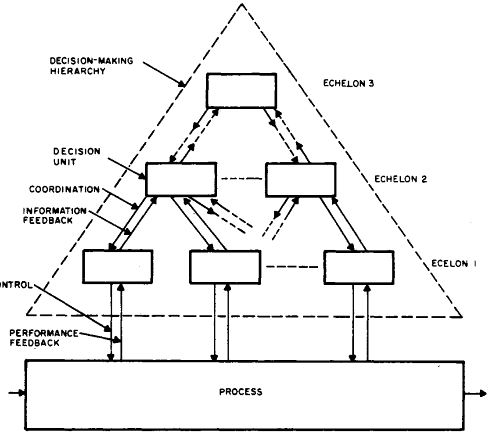


Hierarchical Control Structure

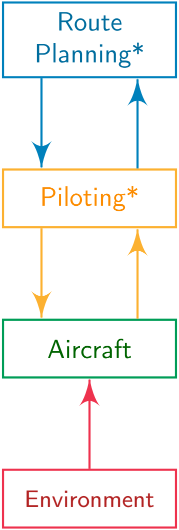
How to Establish Hierarchy?

- Higher level of systems:
  - Decision Making Priority
  - Decision Complexity, ↑
  - Time Scale between decisions, ↑
  - Dynamics of controlled system, ↓



Hierarchical Control Structure

Function



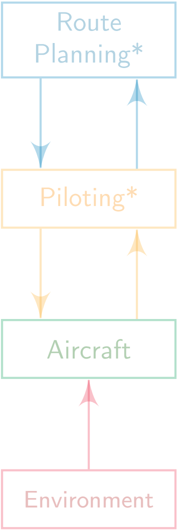
Safety-Related Responsibilities

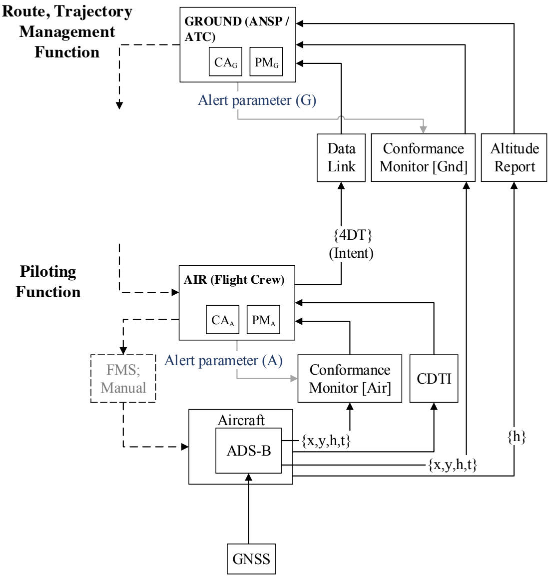
- Provide conflict-free clearances & trajectories
- Merge, sequence, space the flow of aircraft

- Navigate the aircraft
- Provide aircraft state information to rte planner
- Avoid conflicts with other aircraft, terrain, weather
- Ensure that trajectory is within aircraft flight envelope

- Provide lift
- Provide propulsion (thrust)
- Orient and maintain control surfaces

Hierarchical Control Structure





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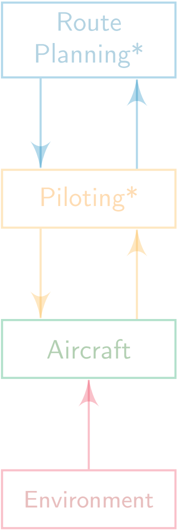

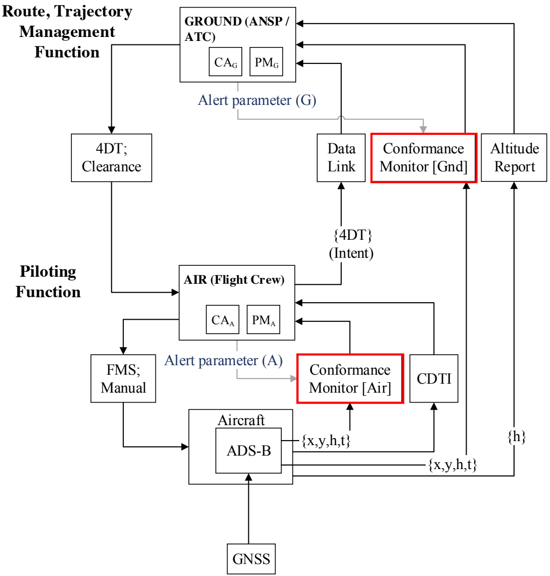

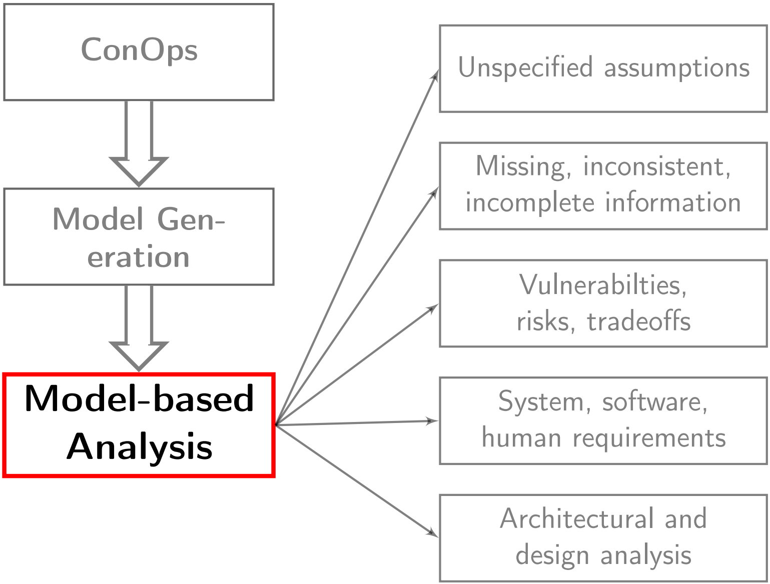
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risks, tradeoffs
System, software,
human requirements
Architectural and
design analysis

Analysis

1. Are the control loops complete?
2. Are the system-level safety responsibilities accounted for?
3. Do control agent responsibilities conflict with safety responsibilities?
4. Do multiple control agents have the same safety responsibility(ies)?
5. Do multiple control agents have or require process model(s) of the same process(es)?
6. Is a control agent responsible for multiple processes? If so, how are the process dynamics (de)coupled?

"Completeness"

"Analyzing Safety-related Responsibilities"

"Coordination & Consistency"

Safety-Related Responsibilities

2. Are the system-level safety responsibilities accounted for?

3. Do control agent responsibilities conflict with safety responsibilities?

Safety-Related Responsibilities

- Gaps in Responsibility (2)
- Conflicts in Responsibility (3)

$$(\forall \sigma_i \in \Sigma)\,(\exists \mathtt{c} \in \mathscr{C})\,[\mathtt{P}\,(\mathtt{c}, \sigma_i)]\,, \tag{2}$$

$$(\forall H_i \in \mathcal{H})\,(\neg\exists \mathtt{c} \in \mathscr{C})\,[\mathtt{P}\,(\mathtt{c}, H_i)\;\wedge\;\mathtt{P}\,(\mathtt{c}, \mathcal{G})] \tag{3}$$

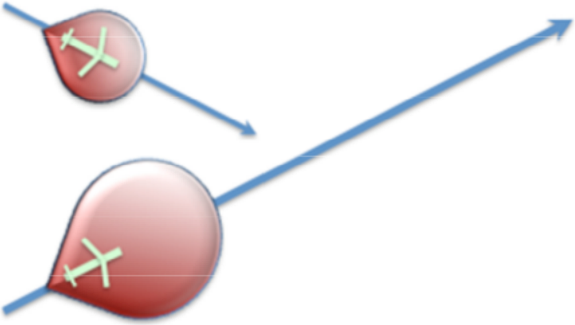
Safety-Related Responsibilities

Potential conflict between goal condition, safety responsibilities???

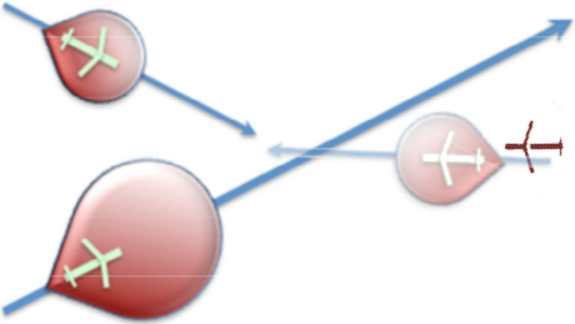
[JPDO, 2011]

"The pilot must also work to close the trajectory. Pilots will need to update waypoints leading to a closed trajectory in the FMS, and work to follow the timing constraints by flying speed controls."

Safety-Related Responsibilities



Safety-Related Responsibilities



Coordination & Consistency

4. Do multiple control agents have the same safety responsibility(ies)?

5. Do multiple control agents have or require process model(s) of the same process(es)?

6. Is a control agent responsible for multiple processes? If so, how are the process dynamics (de)coupled?

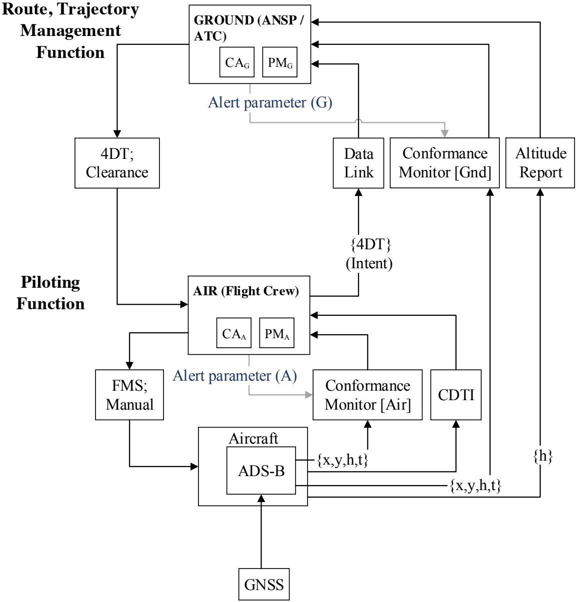
Coordination & Consistency

- Coordination Principle (4)
- Consistency Principle (5)

$$(\forall \mathtt{c} \in \mathscr{C}_i)\,(\forall \mathtt{d} \in \mathscr{C}_j)\,\exists\,(\mathscr{P}\,(\mathtt{c},\mathtt{d}) \vee \mathscr{P}\,(\mathtt{d},\mathtt{c}))\,[\mathtt{A}\,(\mathtt{c},\mathcal{V}_p)\ \wedge\ \mathtt{A}\,(\mathtt{d},\mathcal{V}_p)]\,, \tag{4}$$

$$(\forall v \in \mathcal{V},\, \forall \mathtt{c} \in \mathscr{C}_i,\, \forall \mathtt{d} \in \mathscr{C}_j \mid \mathtt{A}\,(\mathtt{c}, v) \wedge \mathtt{A}\,(\mathtt{d}, v))$$
$$[\rho_i(a,v) \equiv \rho_j(a,v)\ \wedge\ G_i \equiv G_j] \tag{5}$$

Coordination & Consistency



Coordination & Consistency

$$\mathcal{B}_{cm} := \mathcal{L}_{cm} \times D_{cm} \rightarrow \mathcal{I}_{cm}, \tag{6}$$

- $\mathcal{L}_{cm}$ is a model of the airspace state and
- D_{cm} is the decision criteria regarding conformance.

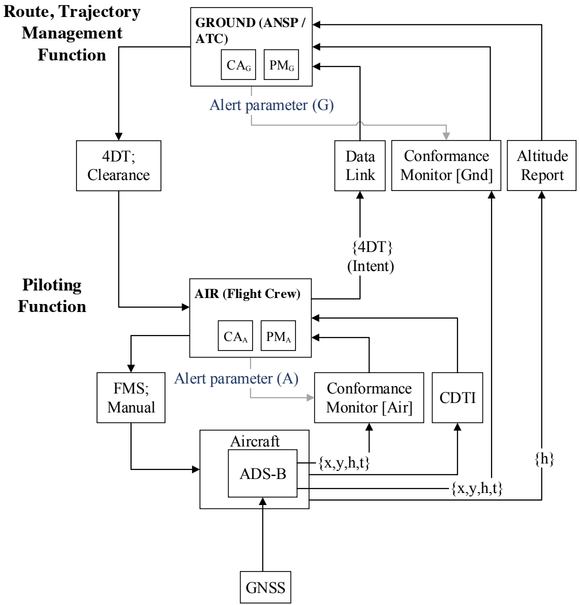
Coordination & Consistency

$$\mathcal{L}_{cm} := \{z_{\text{int}}, z_{\text{act}}, \rho, T, P_r, W, E_{cm}, F_D\} \tag{7}$$

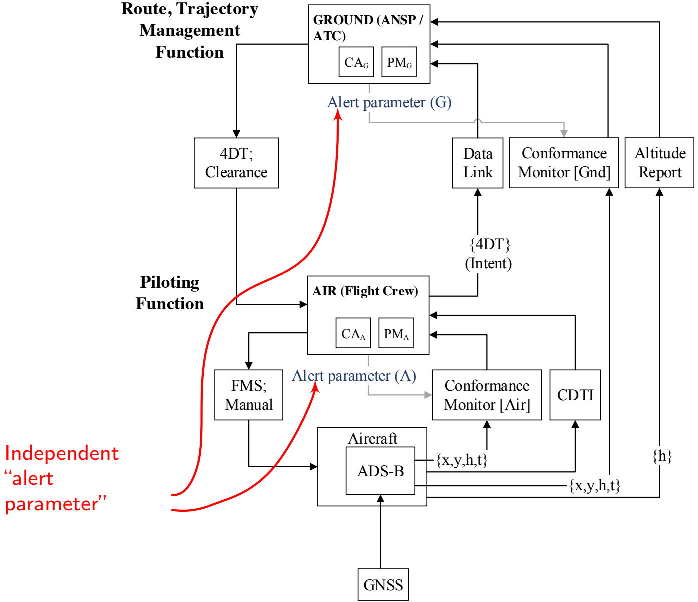
$$\begin{aligned}
z_{\text{int}} &:= \{G, C, t\}_{\text{int}} \\
z_{\text{act}} &:= \{G, C, t\}_{\text{act}} \\
\rho &:= \text{Traffic density} \\
\tau &:= \text{Operation type} \\
P_r &:= \{\text{RNP}, \text{RTP}\} \\
W &:= \text{Wake turbulence model} \\
E_{cm} &:= \text{Elliptical conformance model} \\
F_D &:= \{F, z_{\text{int}}\}
\end{aligned}$$

$$D_{cm} = \{ z_{\text{act}} \mid z_{\text{act}} \notin \bar{z}\left(z_{\text{int}}, E_{cm}, a_{cm}\right)\}, \tag{8}$$

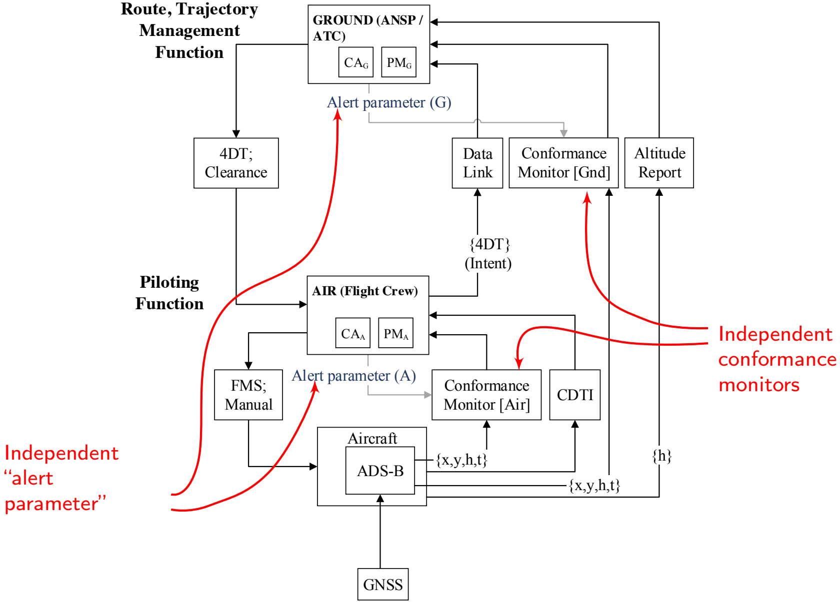
Coordination & Consistency



Coordination & Consistency



Coordination & Consistency



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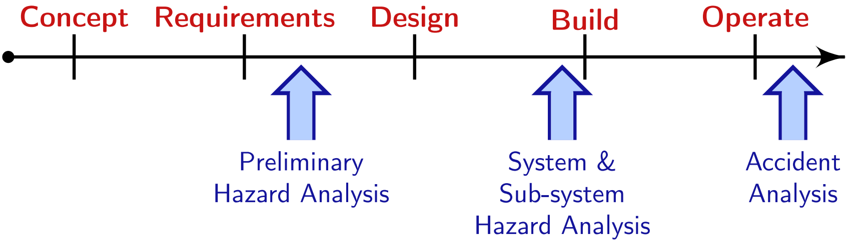
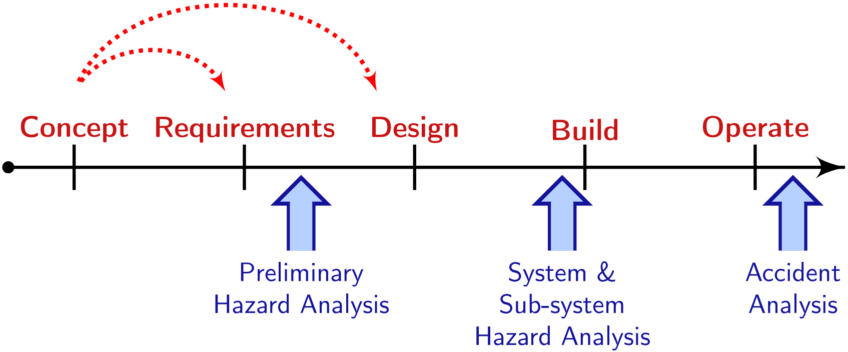
Application of Results

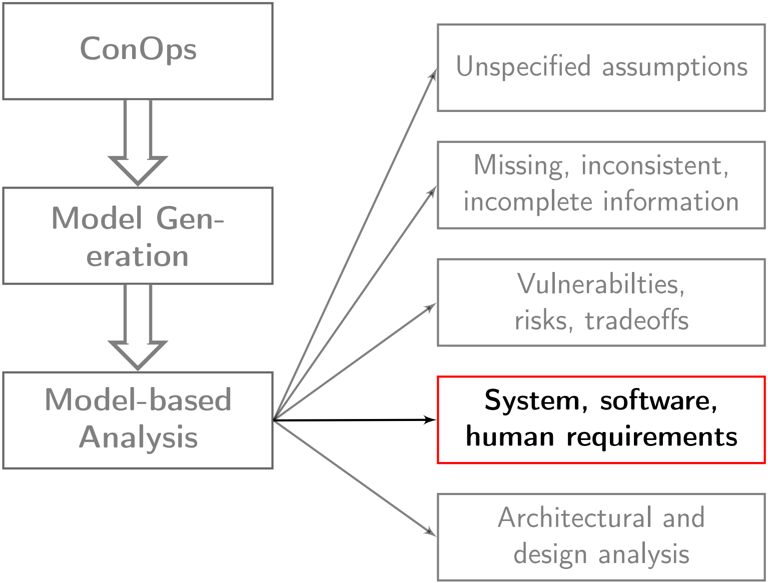


Application of Results

What does an engineer need to develop the system??



Application of Results



Deriving Requirements

Scenario 2:

ANSP issues command that results in aircraft closing (or maintaining) a 4DT, but that 4DT has a conflict.

Causal Factors:

- This scenario arises because the ANSP has been assigned the responsibility to assure that aircraft conform to 4D trajectories as well as to prevent loss of separation.
  - A conflict in these responsibilities occurs when any 4D trajectory has a loss of separation (LOS could be with another aircraft that is conforming or is non-conforming). [Goal Condition]

Deriving Requirements

Scenario 2:

ANSP issues command that results in aircraft closing (or maintaining) a 4DT, but that 4DT has a conflict.

Causal Factors:

- Additional hazards occur when the 4DT encounters inclement weather, exceeds aircraft flight envelope, or aircraft has emergency
- ANSP and crew have inconsistent perception of conformance due to independent monitor, different alert parameter setting
- ...

Deriving Requirements

Scenario 2:

ANSP issues command that results in aircraft closing (or maintaining) a 4DT, but that 4DT has a conflict.

Requirements:

S2.1 Loss of separation takes precedence over conformance in all TBO procedures, algorithms, and human interfaces [Goal Condition]

...

S2.3 Loss of separation alert should be displayed more prominently when conformance alert and loss of separation alert occur simultaneously. [Observability Condition] This requirement could be implemented in the form of aural, visual, or other format(s).

S2.4 Flight crew must inform air traffic controller of intent to deviate from 4DT and provide rationale [Model Condition] ...

Human factors-related requirements

Deriving Requirements

Scenario 2:

ANSP issues command that results in aircraft closing (or maintaining) a 4DT, but that 4DT has a conflict.

Requirements:

S2.8 4D Trajectories must remain conflict-free, to the extent possible

...

S2.10 Conformance volume must be updated within TBD seconds of change in separation minima

S2.11 Conformance monitoring software must be provided with separation minima information

Software-related requirements

Deriving Requirements

Scenario 2:

ANSP issues command that results in aircraft closing (or maintaining) a 4DT, but that 4DT has a conflict.

Requirements:

S2.14 ANSP must be provided information to monitor the aircraft progress relative to its own "Close Conformance" change of clearance

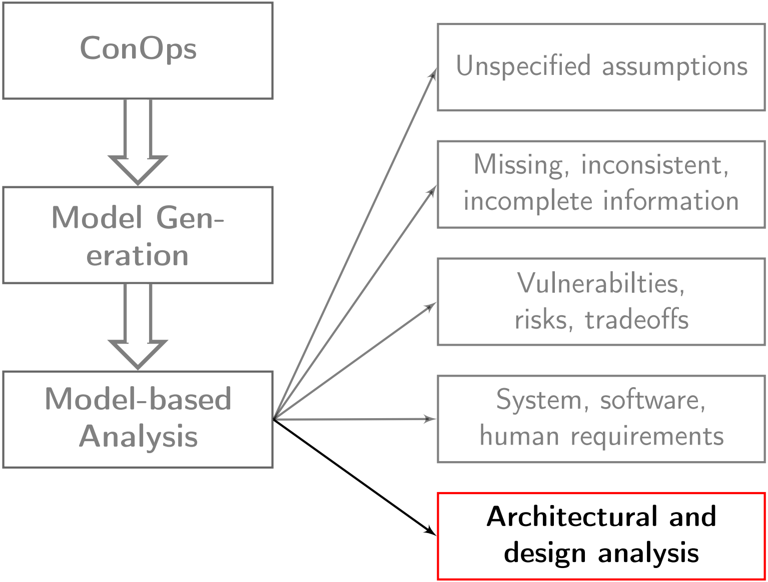
...

S3.2 ANSP must be able to generate aircraft velocity changes that close the trajectory within TBD minutes (or TBD nmi).

Rationale: *TBO ConOps is unclear about how ANSP will help the aircraft work to close trajectory. Refined requirements will deal with providing the ANSP feedback about the extent to which the aircraft does not conform, the direction and time, which can be used to calculate necessary changes.*

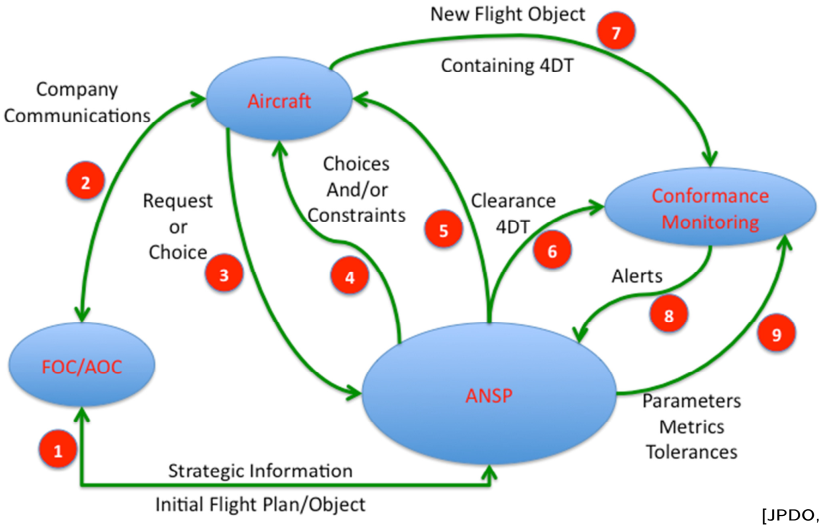
Component Interaction Constraints

Architecture Studies



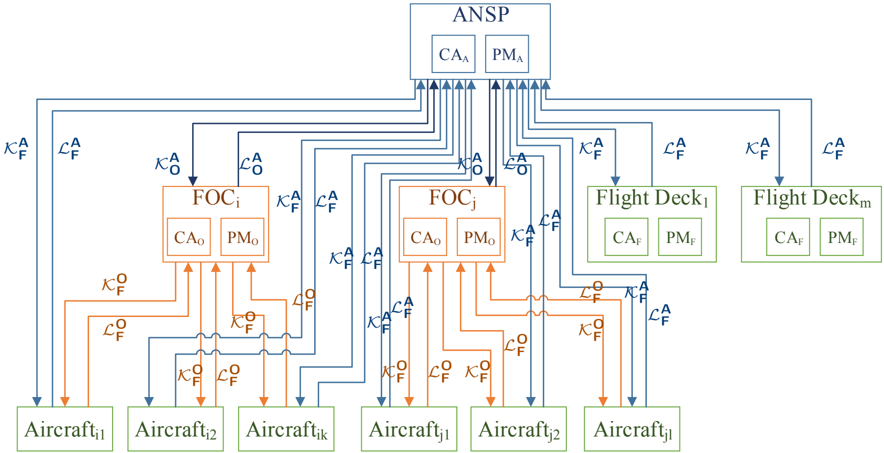
Architecture Studies

Negotiation

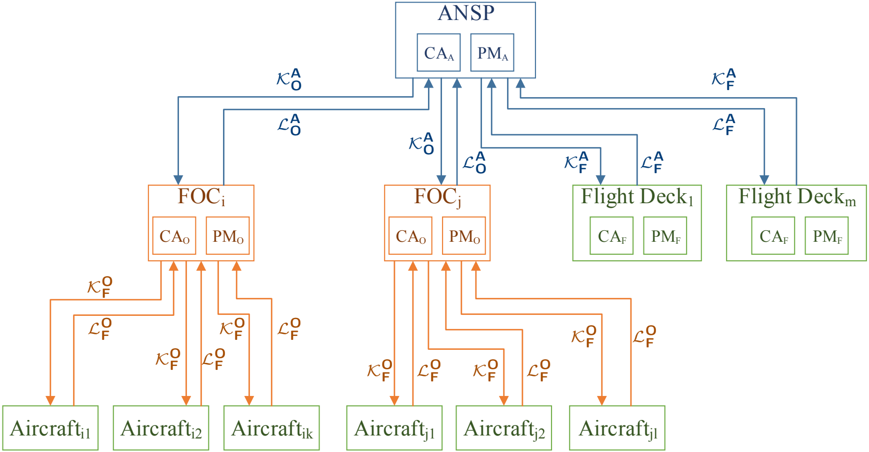


[JPDO, 2011]

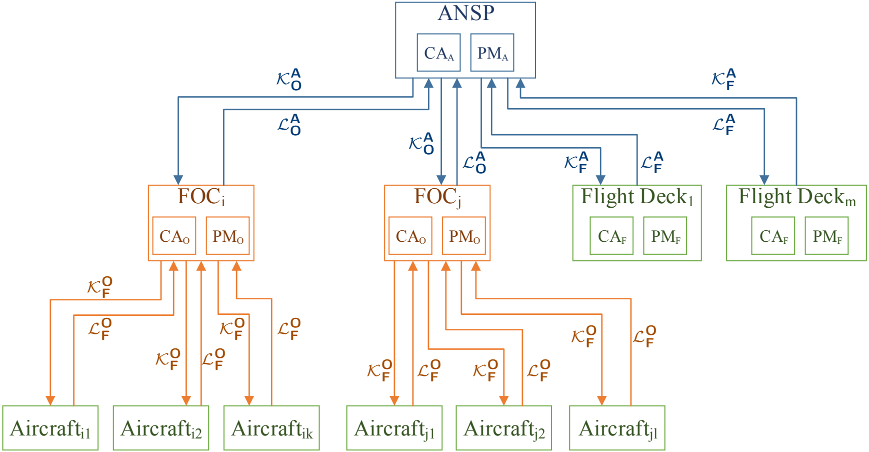
TBO Negotiation



Modified Structure

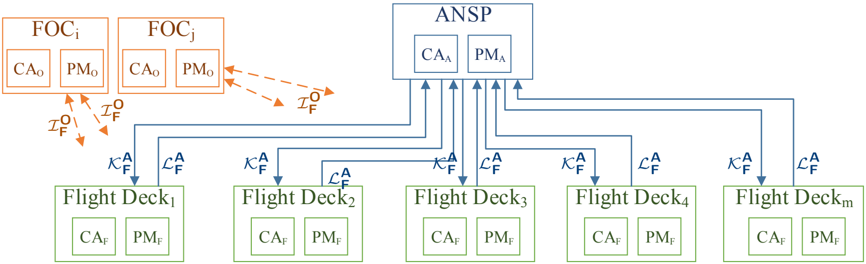


Modified Structure

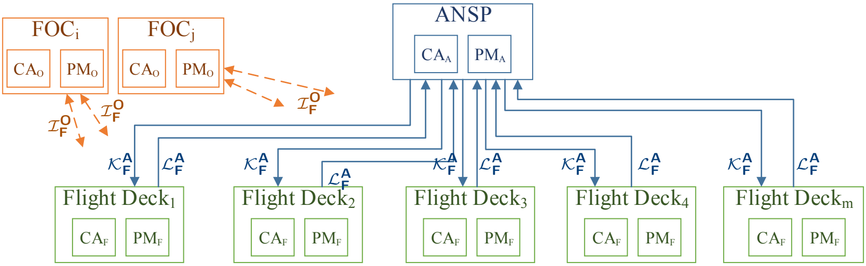


Additional Requirement: $\mathcal{K}_F^A$ and $\mathcal{K}_F^O$ shall *not* occur simultaneously.

Modified Structure

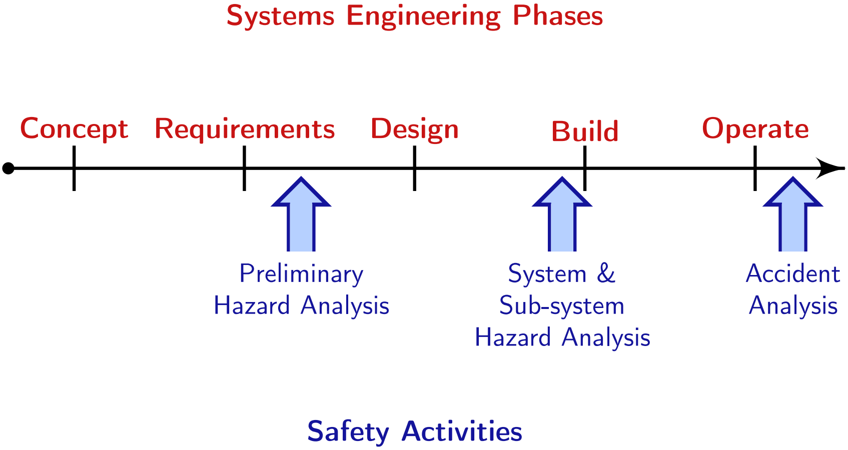


Modified Structure



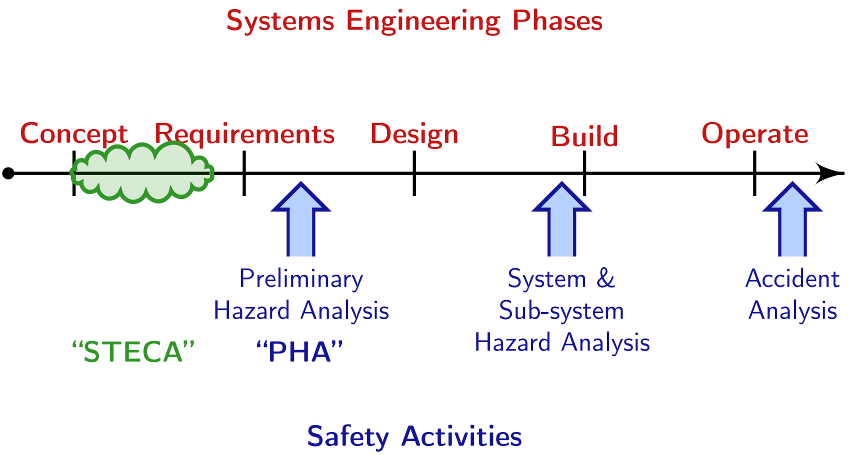
Additional Requirement: This becomes the active control structure within TBD minutes of gate departure.

Evaluation



Systems Engineering Phases
Concept
Requirements
Design
Build
Operate
Preliminary Hazard Analysis
System & Sub-system Hazard Analysis
Accident Analysis
Safety Activities

Evaluation



Systems Engineering Phases
Concept
Requirements
Design
Build
Operate
Preliminary Hazard Analysis
"PHA"
System & Sub-system Hazard Analysis
Accident Analysis
"STECA"
Safety Activities