# Contract-based design and safety analysis of an aircraft wheel brake system: Revisiting AIR6110 with formal methods

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# Version History

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# Contents

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# 1 Purpose of the document

The purpose of this document is to report experiences and insights from a case study that integrates formal methods into an existing design process for safety critical systems. The case study and design process are based on the specification and design of an aircraft Wheel Brake System (WBS), as described in Aerospace Information Report (AIR) AIR6110 [25].

**Context** As aerospace systems become more complex and integrated, it becomes increasingly important that the development of these systems proceeds in a way that minimizes development errors. Advisory Circular (AC) 20-174 [13] from the FAA specifies the Society for Automotive Engineering (SAE) guidance, Aerospace Recommended Practice (ARP) ARP4754A [24], "Guidelines for Development of Civil Aircraft and Systems," as a method (but not the only method) for developing complex systems. ARP4754A along with its companion ARP4761 [23], "Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment," provide the guidance that Original equipment manufacturers (OEMs) such as Boeing and Airbus may utilize to demonstrate that adequate development and safety practices were followed, and that final products meet performance and safety requirements while minimizing development errors.

System safety is a development process compatible with ARP4761 which ensures that system architectures meet functional and safety requirements. Architecture decisions take system functions and safety into account through the use of countermeasures to faults such as redundancy schemas, fault reporting, maintenance, and dynamic system reconfiguration based on fault detection, isolation, and recovery (FDIR). The role of safety assessment is to evaluate whether a selected design is sufficiently robust with respect to the criticality of the function and the probability of fault occurrence. For example, functions with catastrophic hazards must not have any single failure that can result in that hazard. Also, each level of hazard category (viz., catastrophic, hazardous, major, minor, or no safety effect) has an associated maximum probability that must be ensured by the design. For all functions, the system architecture and design must support availability and integrity requirements commensurate with the functional hazards. Among the various analyses, the construction of fault trees is an important practice to compare different architectural solutions and ensure a compliant design.

**The AIR6110 document** AIR6110 [25] is an informational document issued by the SAE that provides an example of the application of the ARP4754A and ARP4761 processes to a specific aircraft function and implementing systems. The non-proprietary example of a wheel brake system (WBS) in this AIR demonstrates the applicability of design and safety techniques to a specific architecture. In this example, The WBS comprises a complex hydraulic plant managing two landing gears each with four wheels and controlled by a redundant computer system with different operation modes. The WBS provides symmetrical and asymmetrical braking and anti-skid capabilities. AIR6110 steps the reader through a manual process leading to the creation of several architectural variants satisfying both functional and safety requirements, and cost constraints.

**Contribution** The work described in this technical report focuses on employing formal methods in the context of a significant aircraft system, as described in the referenced standards documents and with additional industrial requirements.

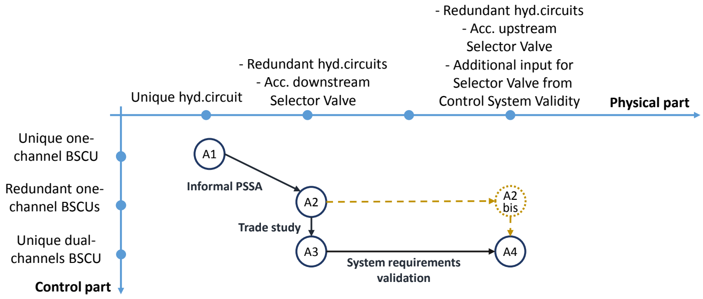
Specifically, the informal process employed in AIR6110 is examined and enhanced using a thorough, formal methodology. We show how formal methods can be applied to model and analyze the case study described in AIR6110. These formal methods support multiple phases of the process, explore the different architectural solutions, and compare them based on automatically produced artifacts.

The approach integrates several formal techniques, including contract-based design, functional verification, fault extension and safety assessment. Integration of the formal techniques is achieved through the use of corresponding support tools (OCRA [7], nuXmv [2], and xSAP [18]) developed by the Fondazione Bruno Kessler (FBK). The resulting analyses include an assessment of the fidelity and effectiveness with which the formal approaches mimic and support the informal process, as well as the scalability of the formal methods to a real-world application of some size and complexity.

The work is the result of a Boeing and FBK joint project, aimed at the evaluation and transfer of automated formal methods in an industrial setting.

**Distinguishing features** The work described in this document is important for several reasons. First, it describes a fully-automated analysis of a complex case study, covering not only the formal modeling and the functional verification but also safety assessments. Second, we propose the integration of different formal techniques (e.g., architectural decomposition, contract-based design, model checking, model-based safety analysis, and contract-based safety analysis) within an automated, unifying flow, which we analyze in terms of scalability and accuracy. Finally, we report interesting results from the standpoint of the AIR6110. Specifically, we provide qualitative and quantitative analyses of the WBS, through an examination of the respective merits of the various architectures. We also show that a flaw affects more architectures than reported in AIR6110.

**Plan of the technical report** This document is organized as follows. In Section 2 we present an informal account of the Wheel Brake System (WBS) application. This includes the technical details of the WBS and the informal process presented in [25]. The development process through several architectural solutions is explained with justifications for design choices leading from each architecture instantiation to the next. An overview of the architecture development, organized according to the structure of the Control and of the Physical system, is depicted here (in blue):


- Redundant hyd.circuits
- Acc. upstream Selector Valve
- Additional input for Selector Valve from Control System Validity
- Redundant hyd.circuits
- Acc. downstream Selector Valve
Unique hyd.circuit
Physical part
Unique one-channel BSCU
Redundant one-channel BSCUs
Unique dual-channels BSCU
Control part
A1
Informal PSSA
A2
A2 bis
Trade study
A3
System requirements validation
A4

In Section 3 we describe the approach adopted to apply formal techniques to analysis of selected architectures. First, contract-based design, supported by OCRA, was used to model architectural decomposition, and to delegate the top-level requirements into contracts for the components. Second, state machine implementations, expressed in nuXmv language, were provided for each of the components. The implementations proved to satisfy their respective contracts, thus obtaining a compositional proof of correctness. A monolithic behavioral implementation of the system was also obtained. Finally, instructions for fault extension were provided, and an extended model generated with xSAP.

In the remaining sections, we detail the modeling and analysis of the five architectures. In Section 4, we consider the modeling and the requirement translation of the architectures of the WBS. Then, in Section 5, we present the results of the formal verification and fault tree generation from the different architectures.

In Section 6 we draw conclusions, lessons learned and outline the directions for future activity.

# 2 The Wheel Brake System in AIR6110

ARP4754A [24] and ARP4761 [23] define recommended practices for development and safety assessment processes for the avionics field. While these defined practices do not have the force of law or regulation, the practices prescribed by these documents are recognized by the Federal Aviation Administration (FAA) as acceptable means for showing compliance with federal regulations [13, 14], and have been used by the industry of the field for years.

The AIR6110 document was released by SAE in 2011. It describes the development of the Wheel Brake System for a hypothetical aircraft following the principles defined in ARP4754A, and show the relationships with the ARP4761.

In this section we present the Wheel Brake System (WBS) case study, based on information in the AIR6110 document and expert clarifications. In Section 2.1, we present an overview of the aircraft of which the WBS is a part. In Section 2.2, we present an overview of the WBS. In Section 2.3, we describe the components of the WBS and in Section 2.4 explain the behavior of the system in more detail. In Section 2.6, we present the process followed by the WBS architecture as described in AIR6110.

## 2.1 Overview of the aircraft

The WBS is part of a hypothetical aircraft, designated model S18. The S18 is a passenger aircraft, with a capacity of 300-350 passengers, capable of a flight duration of approximately five hours. The S18 comprises two engines, two main landing gears and a nose landing gear. Each main landing gear contains four wheels.

The S18 aircraft systems manage nine basic functions:

- *provide structural integrity;*
- *provide stability and control;*
- *provide control of energy;*
- *provide operational awareness;*
- *provide a controlled environment;*
- *provide power generation and distribution;*
- *provide loading, maintenance, ground handling and occupant accommodation;*
- *provide control on the ground;*
- *provide control in the air.*

## 2.2 Overview of the WBS

### 2.2.1 Functions

The WBS manages part of the *"provide control on the ground"* aspect of basic aircraft function. In particular, it fully implements the subfunction *"provide primary stopping force,"* which decelerates the aircraft on the ground. The WBS must ensure the behavior of four leaf functions:

- *decelerate using wheel braking;*
- *provide directional control on the ground through differential braking;*

- *stop main landing gear wheel rotation upon gear retraction;*
- *prevent aircraft motion when parked.*

An overview of the functions covered by the WBS is given in Figure 1, based on the understanding of AIR6110. **The case study used in this document takes into account two leaf functions: *"Decelerate using wheel braking"* and *"Provide directional control on the ground through differential braking"*.**

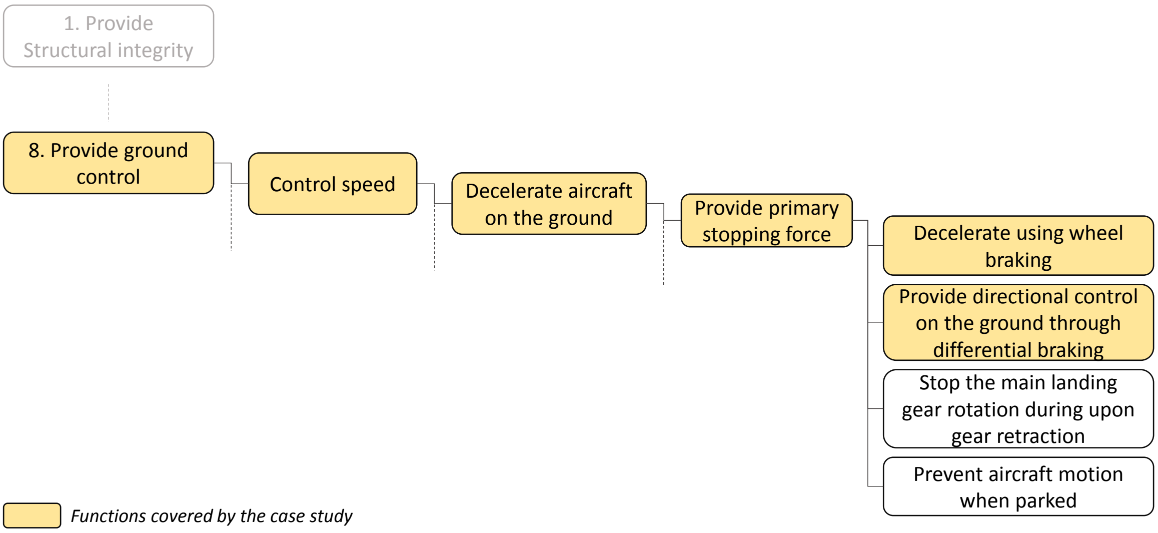

1. Provide Structural integrity
8. Provide ground control
Control speed
Decelerate aircraft on the ground
Provide primary stopping force
Decelerate using wheel braking
Provide directional control on the ground through differential braking
Stop the main landing gear rotation during upon gear retraction
Prevent aircraft motion when parked
Functions covered by the case study

Figure 1: Functional decomposition of the case study

### 2.2.2 Structure

The WBS manages the brakes on the eight wheels of the two main landing gears. The nose gear is unbraked. The WBS receives hydraulic and electric power, and displays information to the crew. To enable these features, it interfaces with systems associated to other functions:

- the hydraulic and electric power plants, which cover the *"provide power generation and distribution"* function;
- the display system, which covers the *"provide operational awareness"* function.

An overview of the WBS is given Figure 2.

## 2.3 Composition

The WBS is composed of a physical system and a control system. The physical system includes hydraulic circuits running from hydraulic pumps to wheel brakes and thus providing braking force to each of the 8 wheels. The physical system can be electrically controlled by the control system, or mechanically controlled directly through the pedals' mechanical position. Each of these systems is also composed of multiple elements. Below we briefly describe these elements. For additional details, see Appendix A.

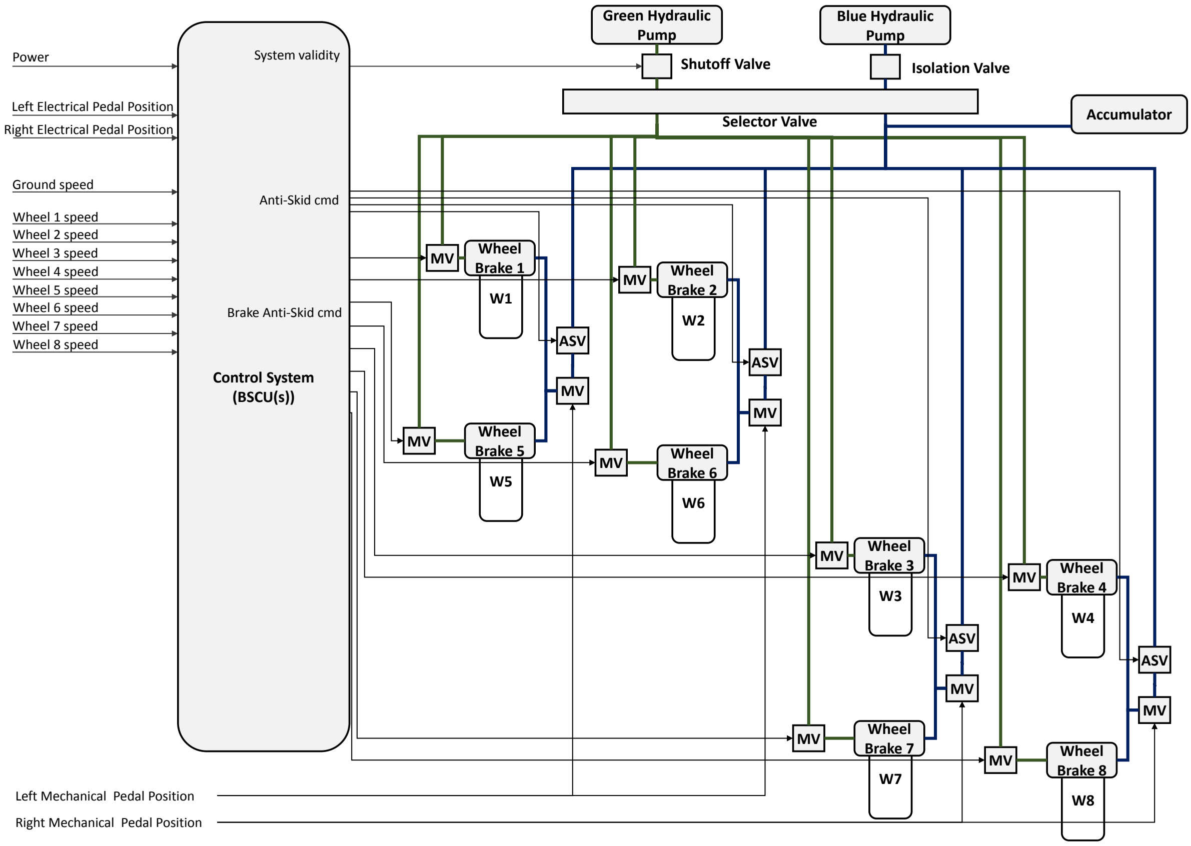


Figure 2: WBS architecture overview (MV=Meter Valve ; ASV=AntiskidShutoff Valve ; W=Wheel)

### 2.3.1 Hydraulic supply

The WBS is hydraulically powered. Hydraulic pressure is supplied by two sources:

- hydraulic pumps, which supply the WBS hydraulic circuits from the hydraulic power plant of the aircraft;
- an accumulator, which is precharged and can be released to supply the WBS hydraulic circuit in case the pumps malfunction.

### 2.3.2 Controls

The WBS is controlled by the crew in two ways:

- the pilot can command the brakes with pedals, which operate electrically or mechanically;
- an auto-brake function is activated when a threshold value of the aircraft speed on the ground is exceeded.

**The auto-brake function is not taken into account in the case study.** So for purposes of this study the braking of the aircraft may be considered to be controlled by the pilot pedals only.

There are two types of pedal, one left and one right, linked respectively to the left and right landing gear assemblies in order to allow differential braking.

There is a set of pedals each for the pilot and co-pilot, linked so that only one left and one right pedal input is received by the WBS.

For each pedal, the mechanical pedal position is translated as an electric signal by a sensor which is used by a computer in the control system to generate an electrical command for braking. Each pedal also produces a mechanical effect which directly controls the hydraulic circuit through a valve, allowing mechanical braking in case of a failure of the electronic system.

The computer used in the WBS is called the Braking System Control Unit or BSCU. The BSCU provides brake commands and anti-skid commands to the WBS, and directs information to crew displays. Anti-skid (AS) is a command sent to the hydraulic circuit in order to inhibit skidding of the wheel due to too much braking force. The anti-skid command is computed based on the aircraft speed and wheel angular speed. The BSCU also provides information about its validity status to the WBS. The BSCU is further decomposed into a monitor system for managing BSCU status and a command system which creates commands for braking.

### 2.3.3 Valves

The valves permit control of the hydraulic pressure supplied to the brakes in the circuit. There are five types of valve:

- shutoff valve: used to close the circuit;
- isolation valve: used to prevent flow back of hydraulic pressure in some systems;
- selector valve: used to switch from one targeted circuit to another, depending on the hydraulic pressure supplied at its inputs;
- antiskid shutoff valve: used to apply anti-skid function in the circuit. It is electrically controlled;
- meter valve: used to control outgoing hydraulic pressure. The meter valve can be electrically or mechanically controlled, and constitutes the main control on pressure routed to the brake.

### 2.3.4 Brakes

The brake is the element which receives hydraulic pressure and transforms it to a braking force to apply on the wheel. Each brake has three elements: The hydraulic fuse which prevents leaks in the system, the hydraulic piston which transforms incoming hydraulic pressure to an outgoing force, and the brake actuator which transmitd the force from the piston to the wheel.

### 2.3.5 Wheels

Each wheel is linked to a sensor in order to measure angular speed to send to the BSCU for computing the anti-skid command.

## 2.4 Expected behavior

### 2.4.1 Modes

The WBS is in charge of braking the two main landing gears, which means the braking of eight wheels. Each wheel possesses its own brake. To avoid full loss of braking power, redundancies are included in the system and different modes of functioning are employed, as described next. In this configuration, each wheel brake can be supplied by either of two distinct hydraulic

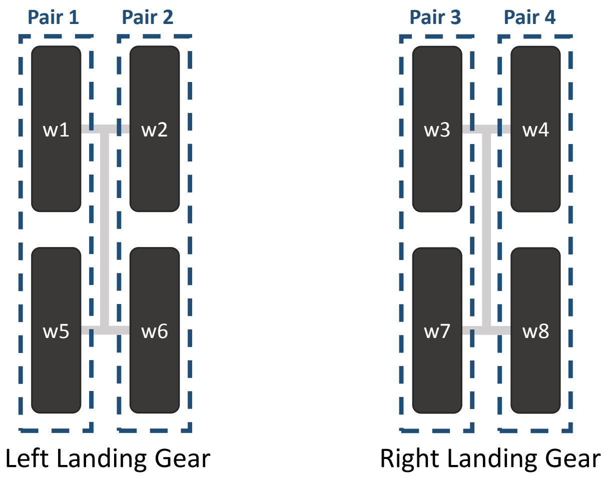


Figure 3: The four pairs of wheels configuration for the Alternate mode

circuits: a green circuit and a blue circuit, each of which is supplied by a separate hydraulic pump.

**2.4.1.1 Normal mode** The green circuit, or Normal Brake system, corresponds to the Normal mode of the WBS. In this mode, the each of the eight wheels is braked separately. Each wheel brake is linked to a meter valve which is controlled by an independent electrical command from the BSCU. This command is the combination of the anti-skid command and the brake command associated with the wheel. The green circuit is composed of eight meter valves.

Switching to the blue circuit is achieved by a selector valve linked to both circuits. This valve is purely mechanical. Depending on the value of the pressure coming from the green circuit, the valve cuts off the supply of the green circuit from the green pump and opens the supply to the blue circuit from the blue pump.

**2.4.1.2 Alternate mode** The blue circuit, or Alternate Brake system, corresponds to the Alternate mode of the WBS. Alternate mode allows mechanical braking of the wheels through the pedal. In contrast to the operation of Normal mode, this mode supports braking of the wheel by pairs. Each wheel is paired with its immediate forward or rearward neighbor, as shown in Figure 3. In Alternate mode, the brake command is mechanical and controls four meter valves, one for each wheel pair. This mode takes into account antiskid commands coming from the BSCU.There are four anti-skid shutoff valves, one for each wheel pair, controlled by the BSCU. Note that operating the Alternate Brake system shall be precluded when the Normal Brake system is in use.

**2.4.1.3 Emergency mode** In addition of the Normal and Alternate mode, a third mode is provided to prevent failure of hydraulic pressure supply to the blue circuit after a failure of supply to the green circuit. This mode is called Emergency mode and is supported by the blue circuit plus an accumulator. The accumulator is pre-charged with hydraulic pressure and is activated only if the hydraulic pressure incoming from the blue pump is below a threshold value. When this condition is met, pressure is released into the circuit, while an isolation valve placed before the pump prevents pressure flowing back. The reserve of the accumulator is supposed to be limited, but sufficient to stop the aircraft on the ground.

| | | Wheel Brake System | | |
|---|---|---|---|---|
| | | Normal | Alternate | Emergency |
| BSCUs | Valid | $\text{Brake}_E$<br>AntiSkid | $\text{Brake}_E$<br>AntiSkid | $\text{Brake}_E$<br>AntiSkid |
| | Invalid | N/A | $\text{Brake}_M$ | $\text{Brake}_M$ |

Figure 4: Braking capacity for each mode

### 2.4.2 Mode switching

The switch from Normal to Alternate mode occurs under two conditions:

- The green pump fails to supply pressure. In this case the selector valve detects low incoming pressure in the green circuit and automatically switches to the blue circuit.
- The BSCU is not valid, and thus the electrical brake commands are not valid. In this case, aircraft braking must be ensured by mechanical commands supported by the blue circuit. The selector valve automatically switches from the green circuit to the blue circuit when it detects lack of pressure in the green one. In front of the selector valve, a shutoff valve is added in the green circuit. This valve automatically cuts off pressure incoming from the green pump if the BSCU is not valid, forcing a switch to the blue circuit.

The switch from Alternate to Emergency mode is made under the condition that the blue pump fails to supply hydraulic pressure.

### 2.4.3 Braking capacity

The braking capacity of the WBS depends on the mode and the validity of the BSCU, assuming that hydraulic supply is always available. In Normal mode, if the BSCU is valid then the pilot can electrically brake and the anti-skid function is active. Otherwise, no braking capacity is available in Normal mode and the system must go into Alternate mode. In Alternate mode, if the BSCU is valid then the pilot can mechanically brake and the anti-skid function is active. Otherwise, only the possibility to brake is available. In the Emergency mode, if the BSCU is valid then the pilot can brake and the anti-skid function is active. Otherwise, only the possibility to mechanically brake is available. A summary is given Figure 4.

## 2.5 WBS requirements

The AIR6110 document contains several requirements for the WBS. These can be grouped in two main categories: Requirements corresponding to safety, e.g., *the loss of all wheel braking shall be extremely remote*, and others, e.g., *the WBS shall have at least two hydraulic pressure sources*.

Below we give five safety requirements we are particularly interested in:

**S18-WBS-R-0321** *Loss of all wheel braking (unannunciated or annunciated) during landing or RTO shall be extremely remote*

**S18-WBS-R-0322** *Asymmetrical loss of wheel braking coupled with loss of rudder or nose wheel steering during landing or RTO shall be extremely remote*

**S18-WBS-0323** *Inadvertent wheel braking with all wheels locked during takeoff roll before V1 shall be extremely remote*

**S18-WBS-R-0324** *Inadvertent wheel braking of all wheels during takeoff roll after V1 shall be extremely improbable*

**S18-WBS-R-0325** *Undetected inadvertent wheel braking on one wheel w/o locking during take-off shall be extremely improbable*

Intuitively, a safety requirement associates the description of an undesirable behaviour or condition (e.g. "inadvertent wheel braking") with a lower bound on its likelihood, according to terminology (e.g. "extremely improbable") that is precisely defined in [1] and a subsequent unreleased "Arsenal" version dated 6/10/2002. The term "extremely remote" corresponds to an average probability to happen per flight hour of order of 1.0e-7 or less and greater than order of 1.0e-9. The term "extremely improbable" corresponds to an average probability to happen per flight hour of order of 1.0e-9 or less.

## 2.6 WBS Architecture evolution

The development of the WBS in the AIR6110 document is described through four evolutionary steps, each step resulting in a specific architecture:

- Arch1: The highest view of the architecture of the WBS comprises one BSCU and one hydraulic circuit backed by an accumulator. This is the first step in the architecture decomposition by defining the main functional elements of system.

- Arch2: This is the basic architecture of the WBS. It includes redundancy principles: There are two BSCUs, a green circuit and a blue circuit. At this step multiple braking modes are introduced.

- Arch3: This evolution of Arch2 replaces the two BSCUs of the control system by one dual channel BSCU.

- Arch4: This evolution of Arch3 modifies the placement of the accumulator and add a link from the control systme validity to the selector valve in the physical system.

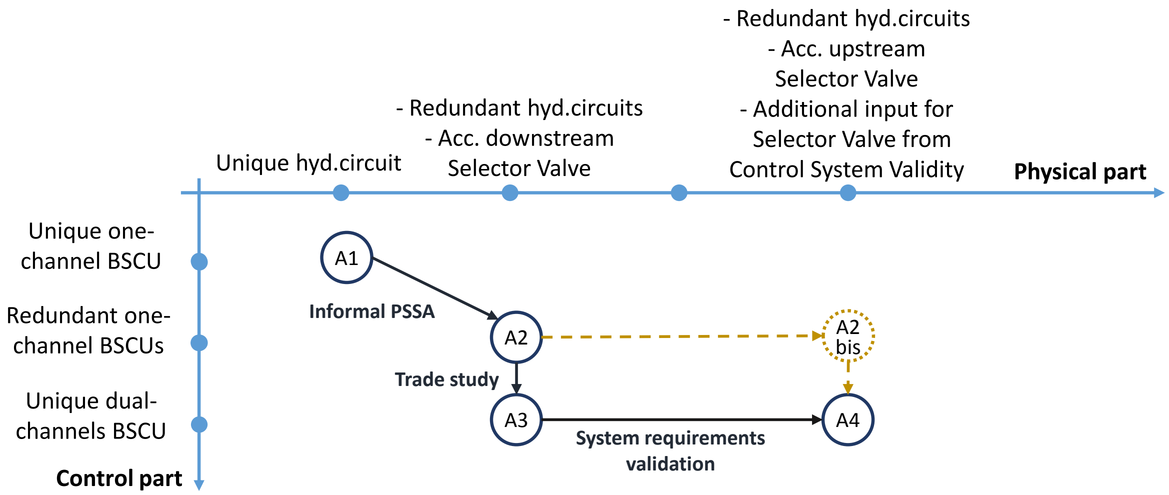
Evolution from one architecture to the next occurs as a result of assessment activities during the development process. A summary of the evolution of the architecture is shown in Figure 5, based on the evolution of the control system and physical system.

The development of Arch2 from Arch1 is motivated by an analysis of safety requirements during an informal Preliminary System Safety Assessment (PSSA). The result of the analysis leads to the addition of two requirements based on service experience, which in turn motivates the presence of redundant design elements in Arch2:

- S18-WBS-R-0508: The wheel braking shall have at least two independent hydraulic pressure sources.

- S18-WBS-R-0509: WBS shall have dual channel BSCU and multimode brake operations to provide the required redundancy.

The development of Arch3 from Arch2 is motivated by trade study results. Trade studies show that a dual BSCU is more cost effective and easier to install and maintain than two BSCUs. Note that both architectures Arch2 and Arch3 must ensure the same safety objectives.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Unique dual-channels BSCU
Control part
A1
Informal PSSA
A2
A2 bis
Trade study
A3
A4
System requirements validation

Figure 5: Architecture evolution of the WBS

The development of Arch4 from Arch3 is motivated by system requirements validation using simulation (model based analysis). The validation shows that the derived system requirement from Arch3, *"The accumulator shall be attached to the blue hydraulic line between the selector valve and the Anti-Skid Shutoff valve,"* is in conflict with the pre-existing requirement *S18-WBS-R-2973 "Operation of the alternate system shall be precluded when the NORMAL system is in use"*. This result triggers modifications leading to Arch4.

To this four basic architectures available in AIR6110, we add an architecture variant called Arch2bis which is based on the control system architecture of Arch2 and the physical system architecture of Arch4. The purpose is to show that it is possible to detect the issue that motivated the change to Arch4 earlier in the design process at Arch2.

# 3 Formal process for the case study

In this section, we present the formal approach to model and analyze the case study. In Section 3.1, we present an overview of the process that is applied and the tools employed. Then, we describe in Section 3.2, Section 3.3 and Section 3.4 the detailed steps.

## 3.1 Overview of the process

The process of applying formal methods to the design of the WBS is achieved through specific steps, as shown in Figure 6.

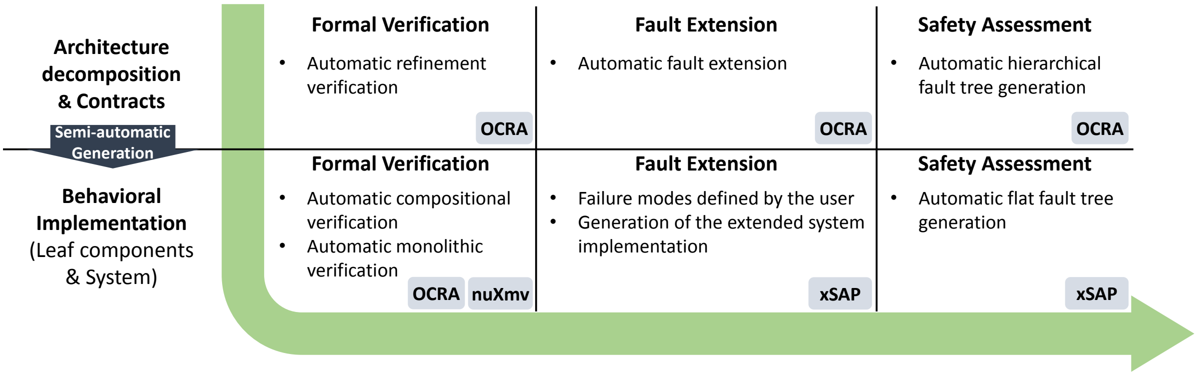

Architecture decomposition & Contracts
Semi-automatic Generation
Behavioral Implementation (Leaf components & System)
Formal Verification
• Automatic refinement verification
OCRA
Fault Extension
• Automatic fault extension
OCRA
Safety Assessment
• Automatic hierarchical fault tree generation
OCRA
Formal Verification
• Automatic compositional verification
• Automatic monolithic verification
OCRA
nuXmv
Fault Extension
• Failure modes defined by the user
• Generation of the extended system implementation
xSAP
Safety Assessment
• Automatic flat fault tree generation
xSAP

Figure 6: Steps of the process

The main steps are: component-based modeling of the system architecture, contract-based specification of the architectural decomposition and refinement verification; definition of the behavioral implementation of components at the leaves of the architecture, generation of the full system implementation and formal verification of the properties; extension of the implementation with failures to include faulty behaviors of components; production of a safety analysis based on fault-tree analysis.

The formal approach is supported by a set of tools developed by the Fondazione Bruno Kessler, namely OCRA [7, 16, 9, 10] for contract-based specification, verification, and safety analysis of the architecture decomposition; nuXmv [2, 15] for formal verification of the behavioral implementation; and xSAP [3, 17, 4] for model-based safety analysis of the behavioral implementation.

## 3.2 Definition and formal verification of the architectural decomposition

The architecture decomposition is expressed in the OCRA language. The system architecture is hierarchically decomposed into constituent components, until leaf components of the system are reached. Each component has an interface defining the boundary between the component implementation and its environment. An interface consists of a set of input and output ports through which the component implementation interacts with its environment. A composite component is refined into a synchronous composition of instances of sub-components. The decomposition also defines interconnections among the ports of the instances of the subcomponents and the composite component. The implementation of a composite component is given by the composition of the implementations of the subcomponents instances. Similarly, the environment of a subcomponent is given by the composition of the other subcomponents.

The specification of a leaf component is described in Listing 1. It is composed of the inputs and outputs of the component. The specification of a refined component is described in Listing 2. It is composed of the inputs and outputs of the component, the list of its sub-components, and the connections between all component instances.

```
COMPONENT Component0
 INTERFACE
  INPUT PORT input1:type1;
  INPUT PORT inputN:typeN;
  OUTPUT PORT output1:type1;
  OUTPUT PORT outputN:typeN;
```

Listing 1: Specification of a leaf component

```
COMPONENT Component0
 INTERFACE
  INPUT PORT input1:type1;
  INPUT PORT inputN:typeN;
  OUTPUT PORT output1:type1;
  OUTPUT PORT outputN:typeN;

 REFINEMENT
  SUB instance_Component1: Component1;
  SUB instance_ComponentN: ComponentN;

 CONNECTION instance_Component1.input:=input1;
 CONNECTION instance_Component2.input:=inputN;
 CONNECTION output1:=instance_ComponentN.output;
 CONNECTION outputN:=instance_Component1.output;
```

Listing 2: Specification of a refined component

Each component is enriched with contracts that expresses its expected behavior. These specifications contributes to the correct refinement and implementation of the system. A contract is composed of an `assume` clause, which represents the property that the environment of the component must ensure, and a `guarantee` clause which describes the property that the component must ensure. The properties in component contracts are formalized into LTL formulas following the Contract-Based Design supported by OCRA. Contracts of refined components are refined by the contracts of their sub-components. It is also possible to write multiple contracts for a given component.

An example of contract is shown in Listing 3. The component, `Component0` has a contract named `contract_component0` and this contract is refined by contracts of the sub-component of `Component0`.

```
COMPONENT Component0
 INTERFACE
  INPUT PORT input1:type1;
  INPUT PORT inputN:typeN;
  OUTPUT PORT output1:type1;
  OUTPUT PORT outputN:typeN;

 CONTRACT contract_component0
  assume: property_1;
  guarantee: propert_2;

 REFINEMENT
  SUB instance_Component1: Component1;
  SUB instance_ComponentN: ComponentN;

 CONNECTION instance_Component1.input:=input1;
 CONNECTION instance_Component2.input:=inputN;
 CONNECTION output1:=instance_ComponentN.output;
 CONNECTION outputN:=instance_Component1.output;
```

```
CONTRACT contract_component0 REFINEDBY instance_Component1.contract_component1,
                                       instance_ComponentN.contract_componentN;
```

Listing 3: example of contract in a component

The refinement of the architecture decomposition can be automatically checked by OCRA by generating and discharging a set of proof obligations that are validity problems for LTL.

### 3.3 Definition and formal verification of the behavioral implementation

OCRA can also automatically generate implementation templates for leaf components of the architecture [1]. Implementation templates are generated in the SMV language [2]. The user needs to provide only the implementations of leaf components in the template, i.e., the `ASSIGN` section. An implementation describes how the outputs of a component are computed from its inputs. An example is given Listing 4.

```
-- ===============================================================================
MODULE main
    VAR
        Component0_inst : Component0(input1, inputN);
    VAR
        output1 : type1;
        outputM : typeM;
    DEFINE
        output1 := Component0_inst.output1;
        outputM := Component0_inst.outputM;

-- ===============================================================================
--                             End of module
-- ===============================================================================

-- ===============================================================================
MODULE Component0(input1, inputN)
    VAR
        output1 : type1;
        outputM : typeM;

    ASSIGN
        output1 := <value or formula depending on inputs>;
        outputM := <value or formula depending on inputs>;
-- ===============================================================================
--                             End of module
-- ===============================================================================
```

Listing 4: example of implementation of a component

Once done, OCRA can take into account these implementations to automatically generate a full system implementation in the SMV language, based on the architecture decomposition[2]. During this generation, the component contracts are automatically translated as LTL properties in the system implementation. Each leaf component implementation can be checked according to the component contracts defined in the architecture decomposition using the compositional implementation check available in OCRA. The full system implementation can also be monolithically checked using the symbolic model checker NUXMV.

### 3.4 Fault extension and safety assessment

The safety assessment can be conducted in two ways. The first, using Model Based Safety Analysis (MBSA), requires the definition of failure modes and model extension but gives precise

[1] with the OCRA command `print_implementation_template`

[2] This is done with the OCRA command `print_system_implementation`

results. The second, using Contract Based Safety Analysis (CBSA), does not require any additional input from the user but gives over-approximated results.

### 3.4.1 Model-Based Safety Analysis (MBSA)

The xSAP tool is used to support the extension a nominal model with failure modes provided by the user. A failure mode represents the behavior of a component in the context of a given failure. Failure modes can be defined from the xSAP fault library using a dedicated language for fault-extension.

An example of failure mode defined for a component is given Listing 5. The extension is defined for each component (`MODULE`). The extension of a component is organized with `SLICE`, that represent a set of failure modes that affect the same output variable of the component. A failure mode (`MODE`) is composed of a name (`MeterValve_FailedClosed` in our example), a probability for the fault to occur(`3.25e-6` in our example), a statement about its dynamic (`permanent` in our example) and its type name (`StuckAtByValue_I` in our example). For each different type of failure mode, there are different data fields to fill (`data`). In the example, the field `term` corresponds to the value or the variable that will be used to modified the value of the affected output variable. `input` and `output` are about the affected variable. `event` allows the user to define a specific condition to specify global dynamics between different failure modes. Note that the Common Cause Analysis (CCA) is also available through the extension but is not presented or used in this case study for the moment.

```
EXTENSION OF MODULE MeterValve

   /-- Description of Fault Slice MeterValve_faults --/
   SLICE MeterValve_faults AFFECTS hyd_pressure_out WITH

     /-- Description of fault mode MeterValve_FailedClosed --/
     MODE MeterValve_FailedClosed {3.25e-6} : Permanent StuckAtByValue_I(
              data term << 0,
              data input << hyd_pressure_out,
              data varout >> hyd_pressure_out,
              event failure);
```

Listing 5: Example of failure mode for a component MeterValve

Once failure modes are defined for each component, xSAP can proceed to the fault extension of the nominal model and generate a new SMV implementation taking into account failure behaviors. This extended model is used to conduct Model-Based Safety Analysis on the system with the help of xSAP. More precisely, xSAP can generate flat fault trees based on this extended model. The fault tree Top Level Events (TLE) are violations of the LTL properties inherited from the contracts provided in the architecture decomposition.

### 3.4.2 Contract-Based Safety Analysis (CBSA)

An alternative way to perform safety analysis is provided by OCRA given the contract-based specification of the architecture [5]. The architecture decomposition is automatically extended with failure modes based on the contracts. The TLEs of fault trees are violations of the system top-level contracts of the architecture. Hierarchical fault tree are generated, with intermediate events being derived from violations of subcomponent contracts. The user does not need to provide any further information beyoned the model itself. In comparison with the flat fault trees generated by MBSA, the hierarchical fault trees are over-approximated.

# 4 Formal models

In this section we present the formal modeling of the WBS. In Section 4.1 we present the modeling hypothesis and abstraction. In Section 4.2 we describe the modeling of the basic components of the architectures. We describe their interfaces, their behavior and their failure modes. In Section 4.3 we give the safety requirements defined in the modeling. We present how they have been translated and we give information about the other properties. In Section 4.4, we describe in the decomposition of each architecture. In Section 4.5 we give metrics about the architecture decompositions and the monolithic models generated from them. We also give metrics about the extended models.

## 4.1 Modeling hypothesis

The WBS architectures presented in AIR6110 are modeled following the formal approach described in the previous section. As a first step to applying formal methods to the case study, we define some modeling hypotheses and we apply simplifying abstractions to the concrete system. First, we consider the hydraulic circuits as a unidirectional circuit, thus avoiding relational modeling of the circuit. As a consequence, the isolation valve present in Figure 2 is not relevant for the modeling and is removed from our formal models. This convention reduces the complexity of the system representation while keeping a level of detail sufficient to express and to verify properties.

Another abstraction concerns the representation of hydraulic pressure in the hydraulic components, for example at the valve interfaces. All ports representing hydraulic pressure are expressed as bounded integers between 0 and 10 (represented as enumeration), as are ports representing braking force. The same representation is used for the aircraft ground speed. A similar abstraction is applied to commands sent by the BSCU. The system validity, the brake commands and the antiskid commands are represented as boolean values. The pedal positions are also treated similarly. The angular speed of a wheel is represented by a wheel status: stopped or rolling. Under this representation, the wheel is considered to be skidding if the aircraft is moving and the wheel is stopped. These choices were made to limit complexity of the models while keeping a sufficient level of detail to obtain relevant results from the analysis.

In addition of these abstractions, we consider two behaviors for pressure supplied to hydraulic circuits. First, a hydraulic pump supplies hydraulic pressure only if the pump is supplied by electrical power and pressurized hydraulic fluid. This allows defining the different mode changes defined in the WBS as depending on the pressure supply of each circuit. Second, the accumulator is considered to have an infinite reserve of pressure. This choice is justified by the fact that the model does not incorporate a concept of measuring “sufficient” pressure necessary to brake the aircraft.

We also consider that the recovery modes are multi-directional. For example, the physical system is allowed to recover from the alternate or emergency mode to the normal mode. The same property is granted to the control system in case of redundancy.

Finally, all models are defined using discrete time and all component behaviors are instantaneous, i.e. all inputs are computed at the same time step where inputs are provided. There is only one exception that concerns the wheel component: braking force applied on the wheel determines the status of the wheel at the next step.

## 4.2 Basic components description

### 4.2.1 FSM components

There are 18 basic components that can be encountered through the different architectures

**Hydraulic Pump** The Hydraulic Pump supplies hydraulic pressure to the hydraulic circuits. In our formal model, the pump has an input corresponding to its electrical power supply and a bounded integer input corresponding its hydraulic supply. If power and hydraulic supply are present, the pump produces an output of an arbitrary hydraulic pressure going from 1 to 10. This variation will be used to simulate the system with various pressure values. The model of the component is presented Figure 7. The white ports represents the inputs and the black ports represents the outputs.

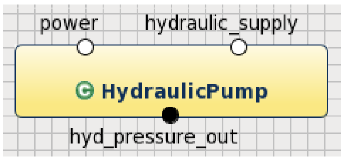


Figure 7: Hydraulic Pump model

**Selector Valve** In the WBS the loss of the hydraulic pressure coming from the green supply can be due to the loss of the green pump or the removal of the pressure by the Control system due to the presence of faults. This loss causes the Selector Valve to automatically connect the blue supply to the Alternate Brake System and to cut the supply to the Normal Brake System.

In our formal model the Selector Valve has two bounded integer inputs corresponding to the pressure supply from the green pump and from the blue pump. It has also two bounded integer outputs corresponding to the pressure supply to the Normal Brake system and to the Alternate Brake system.

If the green pressure supply is greater than zero, then the output to the Normal Brake system is equal to the input from the green pump and the the output to the Alternate Brake system is equal to zero. If the green pressure supply is equal to zero, then the output to the Normal Brake system is equal to zero and the the output to the Alternate Brake system is equal to the input from the blue pump. The model of the component is presented in Figure 8.

A variant of the Selector Valve is made for Arch2bis and Arch4, with an additional boolean input from the Control system validity which will constrain the switch between the circuits.

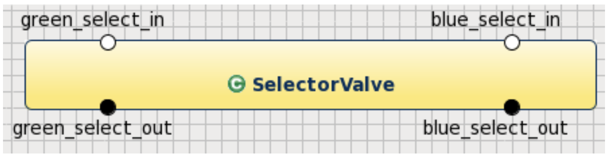


Figure 8: Selector valve model

**Shutoff valve** The Shutoff Valve is used to close the circuit upon an electrical command.

In our formal model, the Shutoff Valve has a bounded integer input corresponding to pressure supply and a boolean input corresponding to the electrical command. The output is a bounded integer corresponding to the pressure out. If the electrical command is received, then the output pressure equals the input pressure. Otherwise, the pressure output equal to zero. The model of the component is presented in Figure 9.

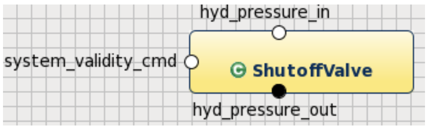


Figure 9: Shutoff Valve model

**Meter valve** The Meter Valve must control pressure to the demanded level. In our formal model it is abstracted so it can only be open or closed. A Meter Valve has two boolean inputs corresponding to an electrical command and a mechanical command. It has one bounded integer input corresponding to the pressure in input. And it has one bounded integer output corresponding to the output pressure.

If an electrical or a mechanical command is received, then the output pressure is equal to the input pressure. If no command is received, the pressure output is equal to zero. The model of the component is presented in Figure 10.

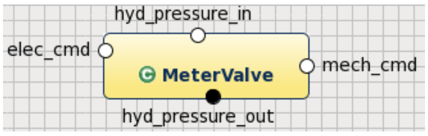


Figure 10: Meter valve model

**Anti-skid shutoff valve** The Antiskid Shutoff Valve is controlled by an electrical command to control the hydraulic pressure. Technically, this valve is used to reduce hydraulic pressure to the brakes in order to prevent locking of the wheels.

In our modeling, it is also abstracted so it can only be open or closed. An Antiskid Shutoff Valve has a boolean input corresponding to an electrical command, a bounded integer input corresponding to the input pressure, and a bounded integer output corresponding to the output pressure.

If an electrical command is received, then the output pressure is equal to zero, otherwise the output pressure is equal to the input pressure. The model of the component is presented in Figure 11.

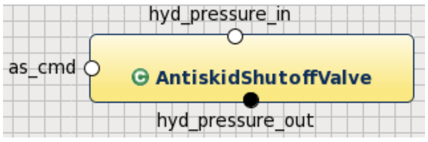


Figure 11: Anti-skid Shutoff Valve model

**Accumulator** In our formal model the Accumulator has a bounded integer input from the blue hydraulic pump and a bounded integer output for the release of the pressure. The pressure input is here to check the pressure coming from the blue pump. If the pressure is equal to zero, then the output pressure of the accumulator is released with a value between 1 and the maximum (10 here). We assume in our formal model that the Accumulator has an infinite reserve. The model of the Accumulator is presented Figure 12.

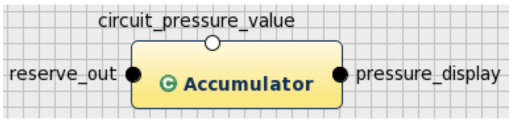


Figure 12: Accumulator model

**Pedal Position Sensor** The Pedal Position Sensor is a sensor which takes in input a mechanical pedal position and returns an electrical position in output. In our formal model it is a direct mapping between a boolean input, the mechanical pedal position, and a boolean output, the electrical pedal position. The model of the component is presented in Figure 13.

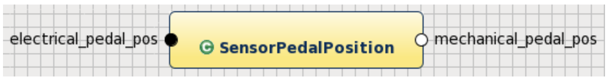


Figure 13: Sensor Pedal Position model

**Hydraulic fuse** The Hydraulic Fuse is here to prevent a leak. In our modeling it is abstracted and corresponds to a simple pipe. It has a bounded integer input corresponding to the input pressure and a bounded integer output corresponding to the output pressure. There is a direct mapping between the input and the output. The model of the component is presented in Figure 14.

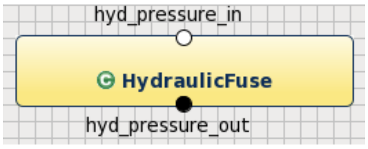


Figure 14: Hydraulic Fuse model

**Hydraulic Piston** The Hydraulic Piston transforms hydraulic pressure into a force to apply to some other component. It has a bounded integer input corresponding to the input pressure and a bounded integer output corresponding to the force created in output. The value of the force in output is equal to the value of the pressure in input. The model of the Hydraulic Piston is presented in Figure 15.

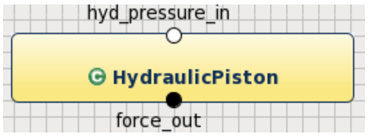


Figure 15: Hydraulic Piston model

**Brake actuator** The Brake Actuator applies the force received from the piston on the wheel: it creates the braking force. Depending on the architectures, it takes one or two bounded integer inputs corresponding to the force transferred by pistons and returns a bounded integer output corresponding to the braking force. The output braking force is equal to the input piston force in case of one source, or is equal to the greater of multiple sources. The model of the component is presented in Figure 16.

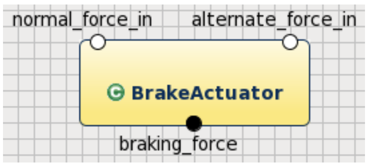


Figure 16: Brake Actuator model

**Wheel** The Wheel is the final component on which the WBS has an influence. It has two bounded integer inputs, the braking force and the aircraft ground speed, and one output corresponding to an enumeration variable indicating its status (rolling or stopped). The behavior of the Wheel in our formal modeling is the following: The Wheel will stop at the next step if the braking force is greater than a threshold value (here 8, chosen arbitrarily) and the ground speed is greater than a minimal value (here 1, chosen arbitrarily); the Wheel will roll at the next step if the braking force is lower or equal to a threshold value and the ground speed is greater than a minimal value; The Wheel will stop at the next step if the ground speed is under a minimal value. The model of the Wheel is presented Figure 17.

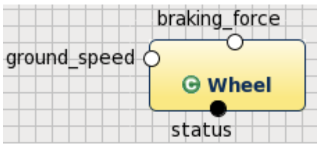


Figure 17: Wheel model

**Wheel sensor** The Wheel Sensor transforms the information received from the wheel into information usable by the Control system. It takes in input an enumeration corresponding to the wheel status (rolling or stopped) and returns a boolean output indicating if the wheel is rolling or not. If the wheel status is rolling, then the output is TRUE, otherwise the output is FALSE. The model of the component is presented in Figure 18.

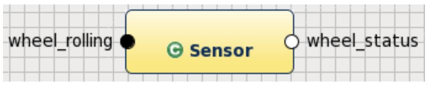


Figure 18: Sensor model

**Monitor System** The Monitor System checks the validity of the commands created and the electrical power supply for the command creation. It returns a boolean output corresponding to the validity of the commands. It takes as inputs all the outputs of the command system (all the commands represented as booleans) and all the inputs of the commands system used to compute these commands (status of each wheel, aircraft ground speed, electrical pedal signal, power) and compares the computations of the commands system with the expected computation. If at least one of these computations is false, the validity output is FALSE. The model of the component is presented in Figure 19.

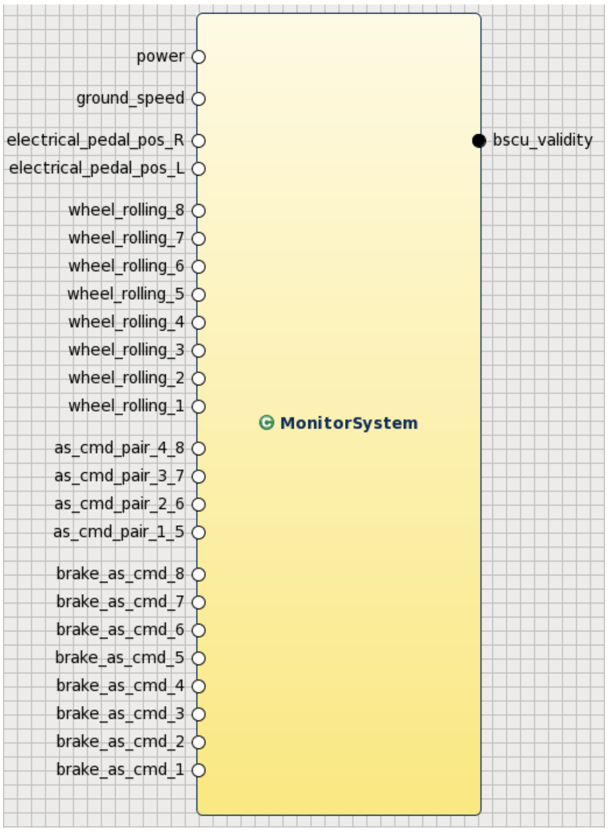


Figure 19: Monitor System model

**Brake Command Facility** This facility computes the brake command for each wheel. It has two boolean inputs corresponding to the power and electrical pedal position And has one boolean output corresponding to the brake command. The outputted brake command corresponds to the conjunction of the power and the electrical pedal position. The model of the component is presented in Figure 20.

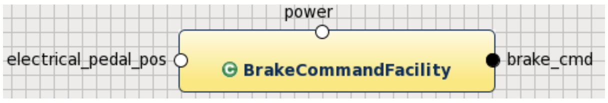


Figure 20: Brake Command Facility model

**AntiSkid Command Facility** This facility computes the antiskid command for each wheel. It has two boolean inputs corresponding to the power and the wheel rolling status, a bounded integer input corresponding to the aircraft ground speed and one boolean output corresponding to the antiskid command. The anti-skid command corresponds to the conjunction of power with a check that the wheel is not rolling and that the aircraft speed is greater than zero. The model of the component is presented in Figure 21.

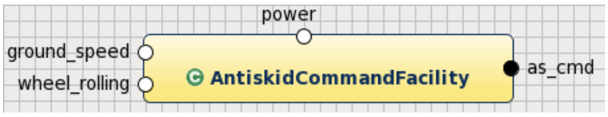


Figure 21: AntiSkid Command Facility model

**Normal Command Calculator** The Normal Command Calculator computes the brake anti-skid command for each wheel and is needed for only some architectures. It takes in input three boolean inputs, the power, the antiskid and the brake command of the wheel. It gives in output a boolean value corresponding to the brake anti-skid command. The brake anti-skid command corresponds to the conjunction of the power, brake command and the negation of the anti-skid command to the wheel. The model of the component is presented in Figure 22.

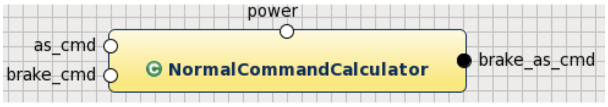


Figure 22: Normal Command Calculator model

**Alternate Command Calculator** In case of a redundant architecture (Arch2, Arch2bis, Arch3, Arch4), this calculator computes the anti-skid commands to send to the alternate brake system for a pair of wheels. It takes in three boolean inputs corresponding to the anti-skid command computed for each wheel and the power, and returns a boolean output corresponding to the anti-skid command to send to the physical system. The anti-skid command computed correspond to the conjunction of the power and the disjunction of the two anti-skid commands received in inputs. The model of the component is presented in Figure 23.

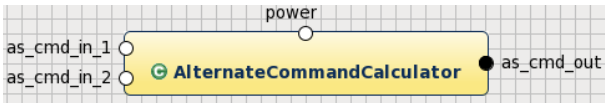


Figure 23: Alternate Command Calculator model

**Switch Gate** The Switch Gate allows deciding between two commands received in inputs, which one to return in output. It takes as input four boolean variables, two corresponding to the commands received in inputs, and two others corresponding to the validity of each source. It has one boolean output corresponding to the returned command. The decision is made as follow: if the source 1 is valid, it is the command of the source 1 that is returned. If the source 1 is invalid and the source 2 is valid, then it is the command of the source 2 that is returned. If both sources are invalid, no command is available as output and the returned value is FALSE. The model of the Switch Gate is presented in Figure 24.

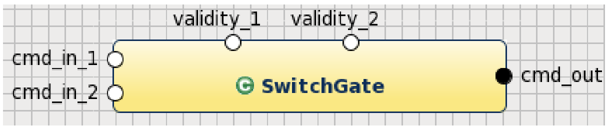


Figure 24: Switch Gate model

In addition of these 18 basic components, we add two others for modeling purpose: Addition Gate and Or Gate.

**Addition Gate** The Addition Gate is a component which takes as input two bounded integers corresponding to two pressure sources and returns a bounded integer output corresponding to the addition of the two pressure sources if lower than or equal to 10 (The max value of all our bounded integers).The model of the component is presented in Figure 25.

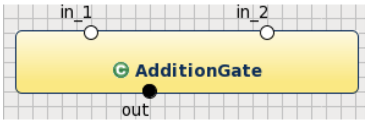


Figure 25: Addition Gate model

**Or Gate** The Or Gate takes as inputs two booleans and returns their disjunction. The model is presented in Figure 26.

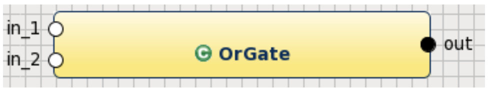


Figure 26: Or Gate model

### 4.2.2 Faults

Possible faults are defined for each leaf components:

- Hydraulic Pumps: Failed off
- Selector valve: Failed last position
- Shutoff valve: Failed open, Failed closed
- Meter valve: Failed open, Failed closed, Failed last commanded position, Failed erroneous position (random)
- Anti-skid shutoff valve: Failed open, Failed closed, Failed last commanded position, Failed erroneous position (random)
- Accumulator: Failed no pressure, Failed stuck open (on)
- Pedal position sensor Undetected erroneous data, no data
- Hydraulic fuse: Failed closed

- Brake piston: Failed stuck at current position, Failed full off, Failed full on
- Brake actuator: Failed stuck at current position, Failed full off, Failed full on
- Wheel: No rotation
- Wheel sensor: Undetected erroneous data, no data
- Monitor System: Erroneous computation
- Normal Command Calculator: Erroneous computation
- Alternate Command Calculator: Erroneous computation
- Brake Command Facility: Erroneous computation
- AntiSkid Command Facility: Erroneous computation
- Switch Gate: Failed last position, Failed intermediate position

Each of these fault is modeled using failure modes from the xSAP fault library. The details are in the fei file of each architecture.

### 4.2.3 Fault probabilities

The probability for each component to be in fault are expressed in and divided for each fault (failure mode). These probabilities are defined based on materials extracted from the AIR6110 and information provided by Boeing.

- Hydraulic Pump, 3.0e-5, only one failure mode
- Shutoff Valve: 1.0e-5, divided by 2 for each of its 2 failure modes (5e-6)
- Selector Valve: 1.0e-5, only one failure mode
- Meter Valve: 1.3e-5 (more complex component), divided by 4 for each of its 4 failure modes (3.25e-6)
- Anti-skid shutoff Valve: 1.3e-5 (more complex component), divided by 4 for each of its 4 failure modes (3.25e-6)
- Accumulator: 1.0e-4, divided by 2 for each of its 2 failure modes (5e-5)
- Hydraulic fuse: 1.0e-5, only one failure mode
- Hydraulic piston: 1.0e-4, divided by 3 for each of its 3 failure modes (3.3e-5)
- Brake actuator: 1.0e-5, divided by 3 for each of its 3 failure modes (3.3e-6)
- Wheel: 1.0e-5, only one failure mode
- All sensors: 1.0e-5, divided by 2 for each of its 2 failure modes (5e-6)
- Monitor System: 8.0e-7, only one failure mode
- Alternate Command Calculator: 9.0e-6, only one failure mode
- Normal Command Calculator: 9.0e-6, only one failure mode

- Antiskid Command Facility: 9.0e-6, only one failure mode
- Brake Command Facility: 9.0e-6, only one failure mode
- SwitchGate: Failed last position: 1.30e-5; Failed intermediate position: 6.50e-7

The rationale to obtain these probabilities is described in the following paragraph.

**Rationale to obtain the fault probabilities for the Physical system leaf components** The fault probabilities for the basic components of the Physical system are based on data provided by Boeing and data from AIR6110 [25, p. 49, Fig. 25], [25, p. 51, Fig. 27].

In particular, the probabilities for the Shutoff Valve, Selector Valve and Meter Valve are based on an evaluation of the probabilities given in the fault trees of AIR6110 [25, p. 49, Fig. 25], [25, p. 51, Fig. 27].

We assume that the fault trees are given for one wheel in the Physical system. In these fault trees the loss of the Green system has a probability of 3.30e-5. If we assume that the loss of Green system is characterized by the loss of the Shutoff Valve or the loss of Selector Valve or the loss of the Meter Valve, we obtain 3.30e-5/3=1.10e-5. And if we consider the Meter Valve as a more complex component, we have the following probabilities for these three components:

- Shutoff Valve: 1.0e-5,
- Selector Valve: 1.0e-5
- Meter Valve: 1.3e-5

We make the assumption that the probability of the Antiskid Shutoff Valve to fail is the same as the Meter Valve. All the other probabilities for the Physical system components have been provided by Boeing.

**Rationale to obtain the fault probabilities for the Control system leaf components** For the BSCU, based on the probability information given in [25, p. 49, Fig. 25], [25, p. 51, Fig. 27] and our model, we made the following rationale to evaluate the reliability of each of its leaf components : in [25, p. 51, Fig. 27], the loss of one BSCU has a probability of 2.17e-4 to happen. We assume that the loss of the BSCU can happen if at least one of its leaf component fails. There are 25 leaf component instances in our model for one BSCU. One of them is the Monitor System and if we follow the allocation given in Figure [25, p. 51, Fig. 27], it has a probability of 8e-7 to fail. If the remaining credit is allocated equally between each instance of the leaf components, we have a probability of 9e-6((2.17e-4 - 8e-7)/24) of failure for each of them:

- Alternate Command Calculator: 9.0e-6
- Normal Command Calculator: 9.0e-6
- Antiskid Command Facility: 9.0e-6
- Brake Command Facility: 9.0e-6

The probabilities for the Switch Gate and the Monitor System to fail are directly taken from [25, p. 51, Fig. 27].

## 4.3 Requirements translation

The five safety requirements expressed in Section 2.5 are translated as contracts at the system top-level. They are modeled as follows: first, we remove flight phase and speed value from the requirements, as we do not have sufficiently detailed information about them in the models. We only kept that the speed value must be greater than 0. The treatment of the required likelihood is ignored in the modeling, and is delayed to the phase of safety analysis. The undesirable condition is instead stated never to occur. In addition, the requirements S18-WBS-R-0322 is split into two different contracts one for the left side and one for the right side. The requirement S18-WBS-R-0325 is also split in eight contracts one for each wheel. Each requirement becomes:

- **S18-WBS-R-0321**: never loss of all wheel braking.
- **S18-WBS-R-0322-left**: never asymmetrical loss of wheel braking (left side).
- **S18-WBS-R-0322-right**: never asymmetrical loss of wheel braking (right side).
- **S18-WBS-R-0323**: never inadvertent braking with all wheels locked.
- **S18-WBS-R-0324**: never inadvertent braking of all wheels.
- **S18-WBS-R-0325-wheelX**: never inadvertent braking of wheel X without locking.

These properties are then translated in LTL form for the contract decomposition. An example of the translation for the property S18-WBS-R-0325-wheelX applied to wheel 1 is given in Listing 6.

```
CONTRACT never_inadvertent_braking_of_wheel_1
assume: true;
guarantee: never((not mechanical_pedal_pos_L) and ground_speed>0
                 and wheel_braking_force_1>0 and wheel_status_1=rolling);
```

Listing 6: Translation of the requirement S18-WBS-R-0325 in contract for wheel 1

In addition, we define sanity properties to validate our modeling at the system top-level. For example, for each wheel we define two properties: first, if there is a braking of the wheel, then a command has been received from the pilot and the anti-skid function has not been applied; second, if a command has been received from the pilot (with a dependency on the anti-skid function), then there is a braking of the wheel.

In the subsequent phase of contract decomposition, these safety requirements are in turn broken down into contracts for sub-components. These contracts describe the properties they must ensure based on the description provided in AIR6110 and clarifications provided by subject matter experts. Additional contracts are also added to ensure the expected behavior of each component (e.g., braking force is applied when commanded). The number of contracts defined on each architecture is given in Table 1 at the end of this section and the contracts are available in the OCRA file of each architecture.

These contracts are then automatically translated into LTL properties in the system implementation, as described in Section 3.3.

## 4.4 Architecture specificities

### 4.4.1 Arch1

Arch1 is the first version of the WBS. This is the most simple view of the system, without any redundancy.

We model Arch1 based on diagram shown inAIR6110 [25, p. 42, Fig. 20] in the Appendix and given clarifications described in Appendix A, Figure 38. For a first look we identify additional sub-system hierarchies to the one defined in the diagrams. The advantages of incorporating additional hierarchies in the system are improved modularity among components and ease of reuse. For example, the decomposition of the Wheel Brake System in a Control system and a Physical system is applicable for Arch2, Arch2bis and Arch3 and Arch4.

The root of the Wheel Brake System is then modeled by two main sub-systems, the Control system and the Physical system. In addition the model includes sensors - 8 wheel sensors and 2 pedal position sensors.

**Control system** The Control system is composed of one unique BSCU. The BSCU of Arch1 create eight brake commands, one for the meter valve of each wheel, and eight anti-skid commands for each anti-skid shutoff valve. The BSCU also generates a validity command for the shutoff valve of the Physical system. The BSCU takes as input its dedicated power source, the electrical pedal positions, the aircraft speed and the status of each wheel.

A BSCU is divided into two sub systems: A Monitor system and a Command system. The Monitor system is in charge of delivering the status and thus the validity of the BSCU, depending on the power consumption and the correctness of the commands computed by the Command System. The Command system is in charge of creating brake and anti-skid commands. The Command system of Arch1 is divided into eight sub-systems, one for each wheel. These systems, called Wheel Command systems, are in charge of creating the brake command and the anti-skid command for each wheel.

The Wheel Command system is decomposed into multiple leaf components, as follows:

- An Antiskid Command facility creates the antiskid command for the wheel, depending on the wheel status and the aircraft speed.
- A Brake Command facility creates the brake command depending on the pedal position.

The type used for commands is boolean, to abstract every command and the presence of electrical power supply. Thus a brake command corresponds to the conjunction of the power and the pedal position. The anti-skid command corresponds to the conjunction of power with a check that the wheel is not rolling and that the aircraft speed is greater than zero.

**Physical system** The Physical system is first composed of an hydraulic pump. This pump supplies the hydraulic circuit with pressure through a Shutoff valve controlled by the Control system validity. An accumulator is placed in back up after the shutoff valve in case the hydraulic pump fails off (Output pressure goes to 0).

The hydraulic circuit is composed of eight Antiskid Shutoff valves that supply eight meter valves. Each pair of Antiskid Shutoff valves and Meter valves is dedicated to one wheel: The Antiskid shutoff valve is commanded by the anti-skid command for the wheel and the meter valve is electrically commanded by the brake command for the wheel or directly by the mechanical pedal position corresponding to the side of the wheel (left or right). Each meter valve then supplies a wheel brake depending on these commands. There is one wheel brake per wheel. A wheel brake takes as inputs the hydraulic pressure coming from the Meter valve and as its output applies a force on the wheel. The Wheel brake of Arch1 is composed of one hydraulic fuse, one hydraulic piston and one brake actuator which makes the link between the pistons and the wheel. Each wheel returns its status and each wheel brake returns the braking force applied to the wheel.

As explained previously, we choose to model a binary behavior for the valve. If the meter valve receives a brake command (electrical or mechanical), it opens and lets the hydraulic pressure supply the wheel brake. If not, it stays closed. If the antiskid shutoff valve receives an anti-skid command, it closes and cuts off hydraulic pressure to the meter valve. If not, it stays opened.

**Sensors** The Wheel sensors provide links between the Control system and the Physical system by giving feedback about the status of each wheel.

The pedal position sensor transform a mechanical signal coming from each pedal into an electrical signal transferring to the Control system.

**Diagram overview** An overview of the upper level decomposition of Arch1 is given in Figures 27, 28, 29 and 30. They describe the decomposition of the architecture from the WBS interface to the decomposition of the Control system and the Physical system. The diagrams are obtained by importing the architecture oss file in the Autofocus[3] tool. The oss file is available in the archive file attached to this report.

A complete overview of the structure of each component of Arch1 are presented in Appendix B.

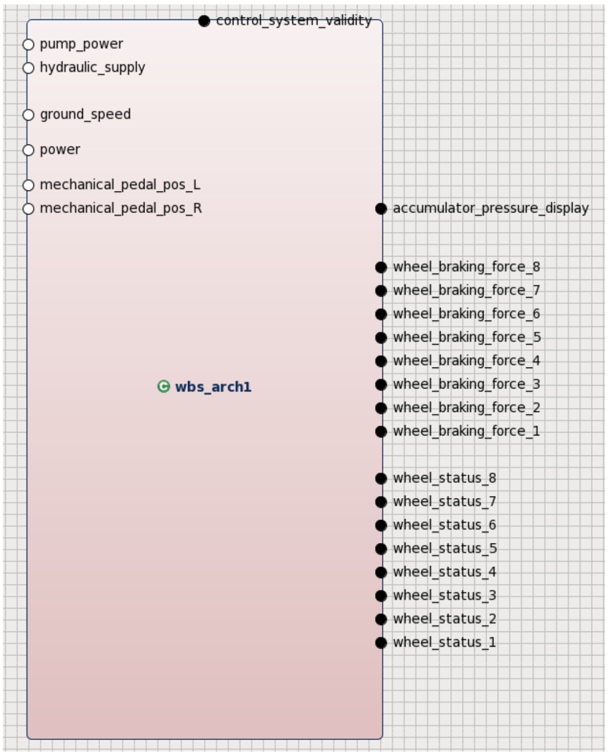


Figure 27: Arch1 environment interface

[3] https://es-static.fbk.eu/tools/autofocra/

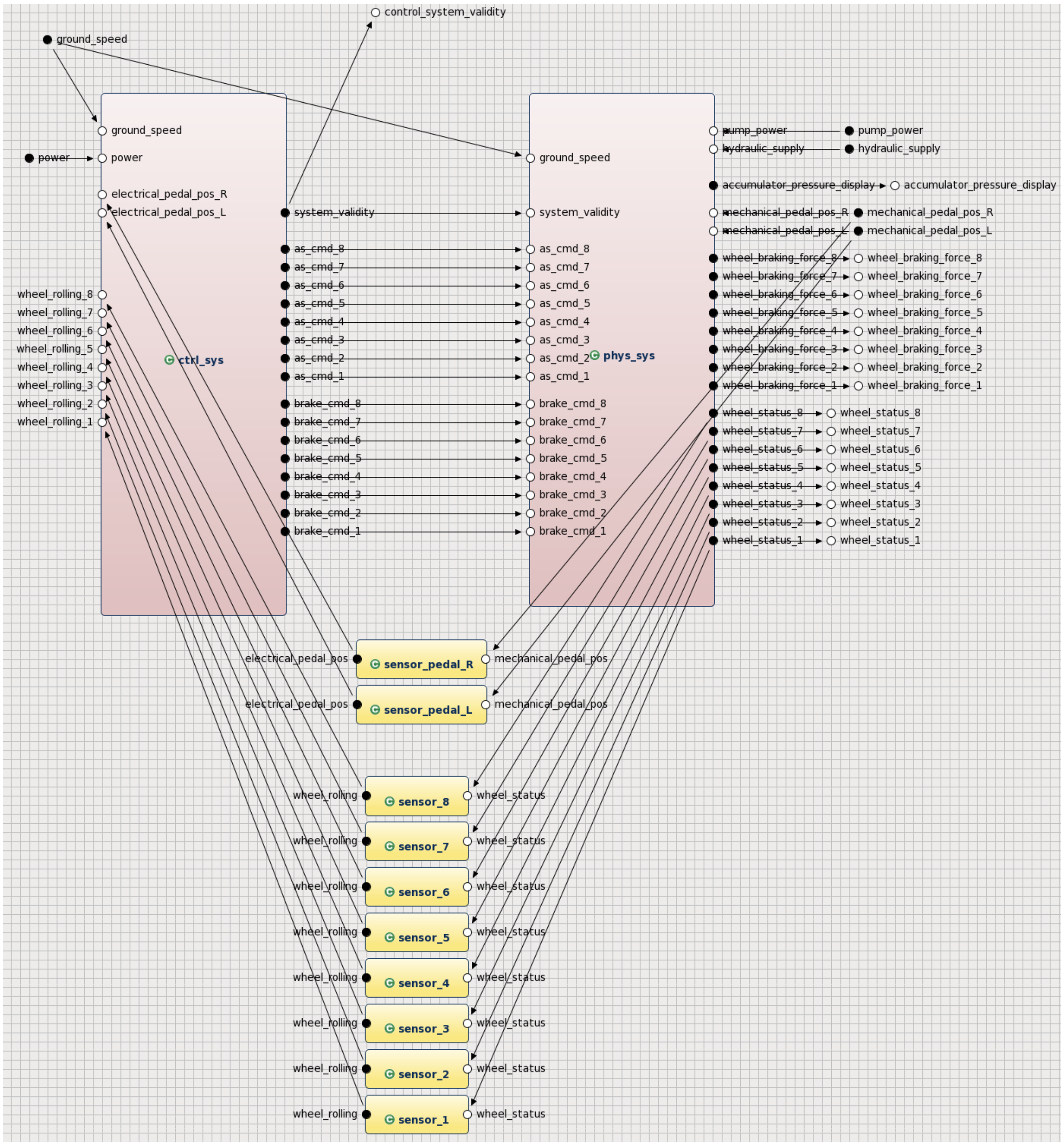


Figure 28: ARCH1 WBS decomposition

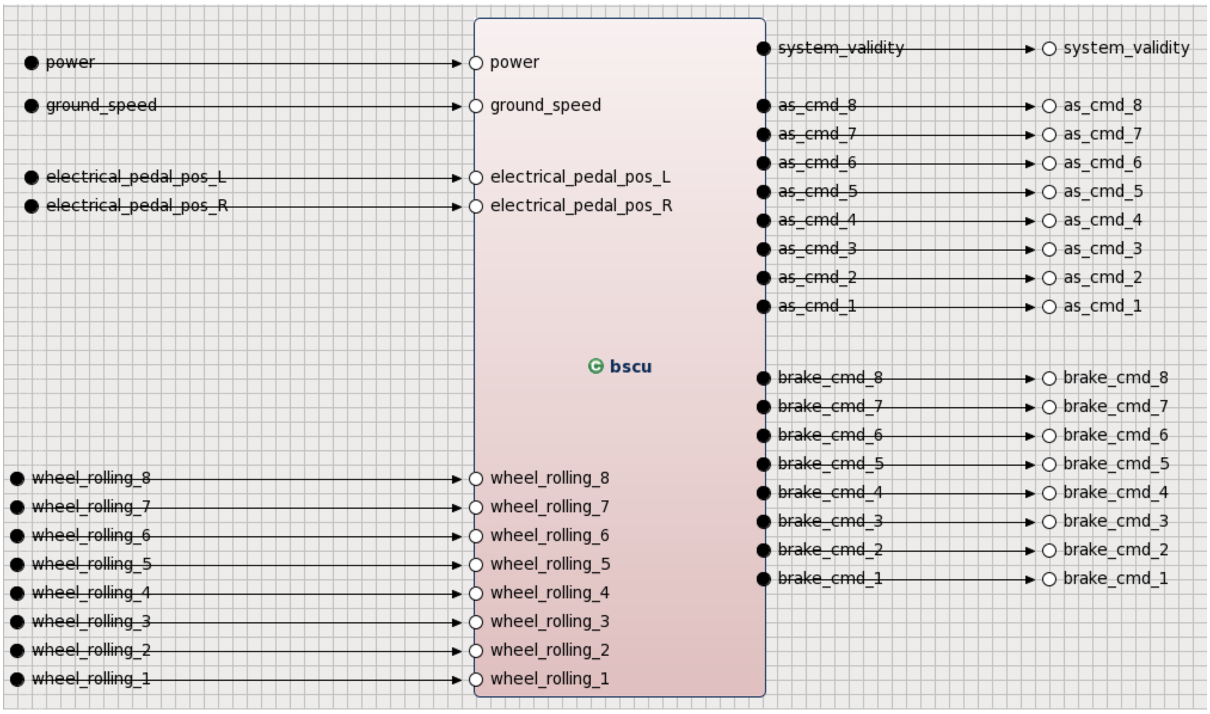


Figure 29: Arch1 Control system decomposition

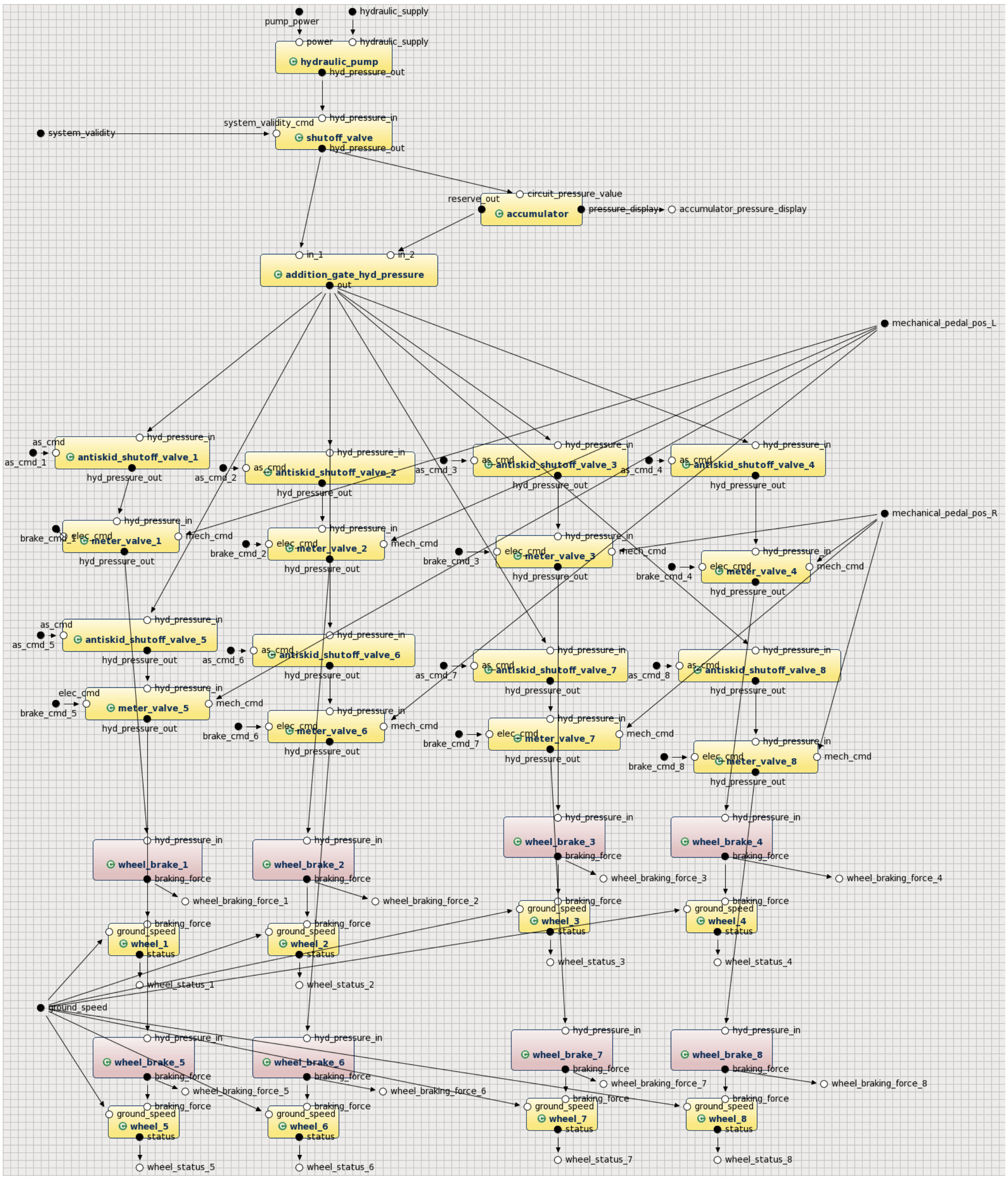


Figure 30: Arch1 Physical system decomposition

### 4.4.2 Arch2

As described in AIR6110 [25, p. 44, Fig. 22], Arch2 is the first version of architecture to include redundancy. Its Control system is composed of two BSCUs and the hydraulic circuit is composed of blue and green circuits as defined in Section 2.4 on the basic expected behavior of the Wheel Brake System.

We model Arch2 based on the diagram shown in AIR6110 [25, p. 44, Fig. 22], and also based on clarifications provided and summarized in Appendix A, Figure 38. We used similar sub-system hierarchies as the one in Arch1: the root of the WBS is modeled by two main sub-systems, the Control system and the Physical system, as well as the sensors, 8 wheel sensors and 2 pedal position sensors.

**Control system** The Control system is composed of two BSCUs and the gates that select commands between them. Each BSCU creates eight brake anti-skid commands, viz., one for the meter valve of each wheel in the Normal Brake system, and four anti-skid commands for the anti-skid shutoff valve of each predefined pair of wheels[4] in the Alternate Brake system. Each BSCU also generates a validity command for the shutoff valve of the green circuit and validity status output information for the crew. Each BSCU takes as input its dedicated power source, the electrical pedal positions, the aircraft speed and the wheel status of each wheel.

The BSCU of Arch2 is divided into two sub-systems, as in Arch1: a Monitor system and a Command system. The Monitor system is in charge of giving the status out and thus the validity of the BSCU. This validity state depends on the power consumption and the correctness of the commands computed by the Command System. The Command system is in charge of creating brake and anti-skid commands. The Command system of Arch2 is different than the one of Arch1: it is divided into four sub-systems, one for each pair of wheels. These systems, called Wheel Pair Command systems, are in charge of creating the brake command and the anti-skid command for each pair of wheels.

The Wheel Pair Command system is decomposed into multiple leaf components as follows:

- An Antiskid Command facility creates the antiskid command for each wheel, based on the wheel status and the aircraft speed.
- A Brake Command facility creates the brake command based on the pedal position.
- An Antiskid Command calculator creates antiskid commands for each pair of wheels in the Alternate Brake system. An Antiskid command is created if at least an anti-skid command is available for one wheel of the pair.
- Two Brake Command calculators create brake/antiskid commands for each wheel.

Finally, the Or gates represented in AIR6110 [25, p. 44, Fig. 22] for merging the commands of the two BSCUs are represented as Switch Gate components in the model. The switch between each BSCU command is realized as following: if the BSCU 1 is valid, it is the commands of BSCU 1 that are sent to the Physical system. If BSCU 1 is invalid and BSCU 2 is valid, then the commands of the BSCU 2 that are sent to the Physical system. If both BSCUs are invalid, no command is sent.

This choice is made to avoid having BSCUs continue to send bad commands if they fail. Indeed, it is not clear in the AIR6110 what happens to the command creation if a BSCU fails, and the basic Or Gate described in the diagram are not sufficient to prevent the Control system to send erroneous commands from an invalid BSCU. This gap has been detected on previous version of our modeling during safety assessment.

The Or gate for merging the two BSCU validity is kept as an Or Gate.

**Physical system** The first components of the Physical system of Arch2 are the hydraulic pumps that supply each circuit: the green pump and the blue pump. The green pump supplies a shutoff valve controlled by the Control system. The shutoff valve is linked to a Selector valve which decides which system to supply. In the Normal mode, the Normal Brake system is supplied by the green pump. The Normal Brake system is divided into eight meter valves, one for each wheel. In this system each of the meter valves are only commanded electrically, unlike in Arch1. The Normal Brake system takes as inputs the eight brake anti-skid commands and supplies each wheel brake depending on these commands. There is one wheel brake per wheel.

[4] wheels 1 and 5, wheels 2 and 6, wheels 3 and 7, wheels 4 and 8

A wheel brake takes as inputs the hydraulic pressure coming from the Normal Brake system and from the Alternate Brake system and as its output applies a force on the wheel. The Wheel brake is composed of one hydraulic fuse and one hydraulic piston for each hydraulic source (normal or alternate), and also one brake actuator which makes the link between the pistons and the wheel. Each wheel returns its status and each wheel brake returns the braking force applied to the wheel.

The blue pump supplies the selector valve. If Normal mode is not available, the selector valve supplies the Alternate Brake system (we chose to model a selector valve which allows return to the Normal mode if it becomes available again). The Alternate Brake system can also be directly supplied by the accumulator if the blue pump cannot supply hydraulic pressure. To support this behavior, the accumulator takes as input the pressure value outgoing from the blue pump. The Alternate Brake system is composed of 4 meter valves and 4 anti-skid shutoff valves. Each meter valve takes in inputs the mechanical pedal position corresponding to the side of the pair of wheels it is linked to (right landing gear or left landing gear), and no electrical command. The Alternate Brake system supplies the eight wheel brakes.

Note that we also define the output of the Physical system - the pressure at the entrance of Selector Valve from the green pump (called `green_pressure_in_selector_valve`). As it is the value that will decide in which mode the WBS is, it allows us to define contracts at the top level depending on the different functioning modes of the WBS.

**Sensors** Similarly to Arch1, the Wheel sensors provide links between the Control system and the Physical system by giving feedback about the status of each wheel.

The pedal position sensor transforms a mechanical signal coming from each pedal into an electrical signal transferring to the Control system.

**Diagram overview** An overview of the upper level decomposition of Arch2 is given in Figure 31, 32, 33 and 34. These figures describe the decomposition of the architecture from the WBS interface to the decomposition of the Control system and the Physical system. The diagrams are obtained by importing the architecture oss file into the Autofocus[5] tool. The oss file is available in the archive file attached to this report.

A complete overview of the structure of each component of Arch2 are presented in Appendix C.

[5] `https://es-static.fbk.eu/tools/autofocra/`

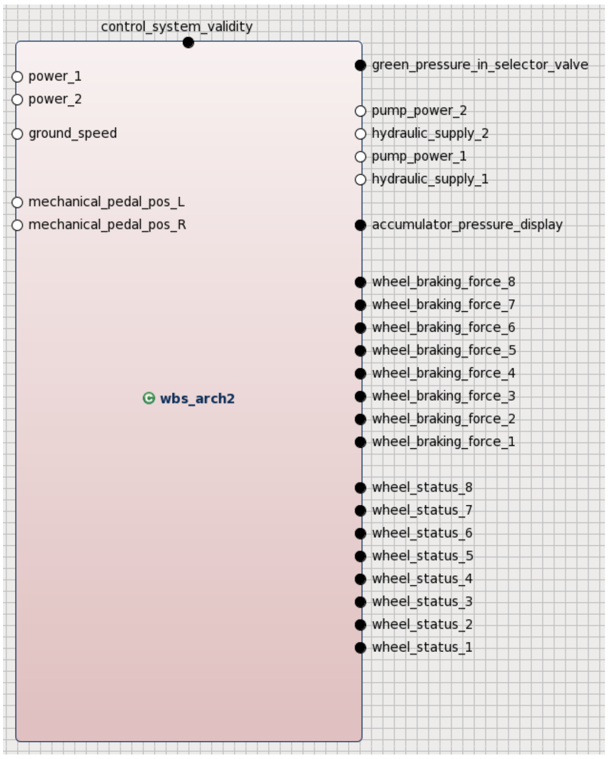


Figure 31: Arch2 environment interface

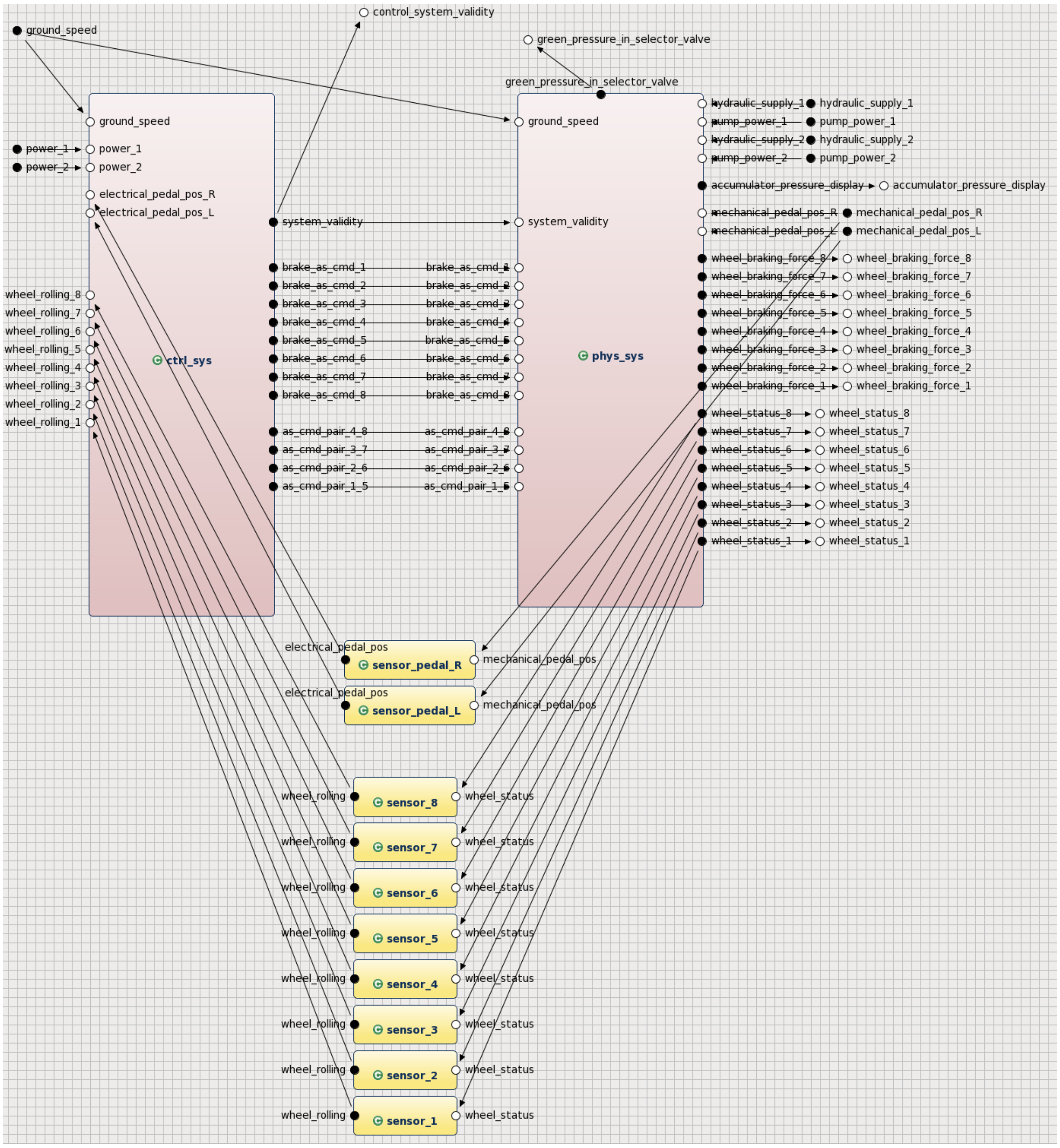


Figure 32: Arch2 WBS decomposition

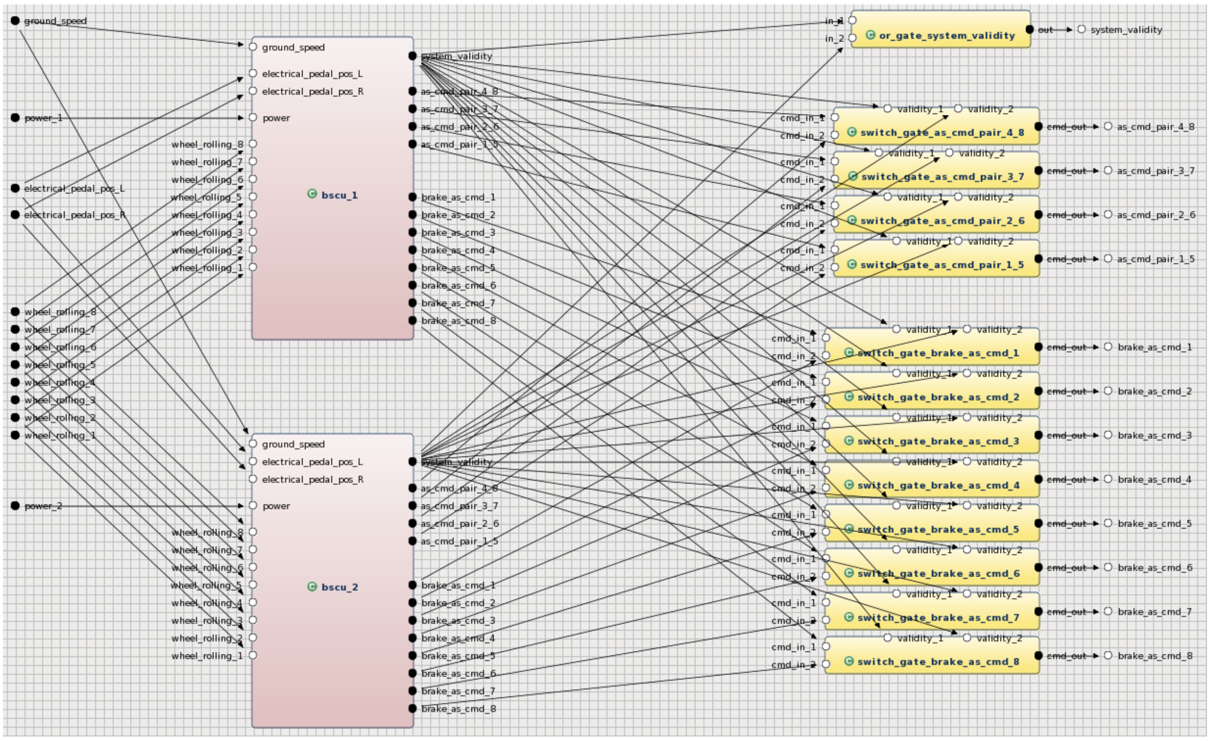


Figure 33: Arch2 Control system decomposition

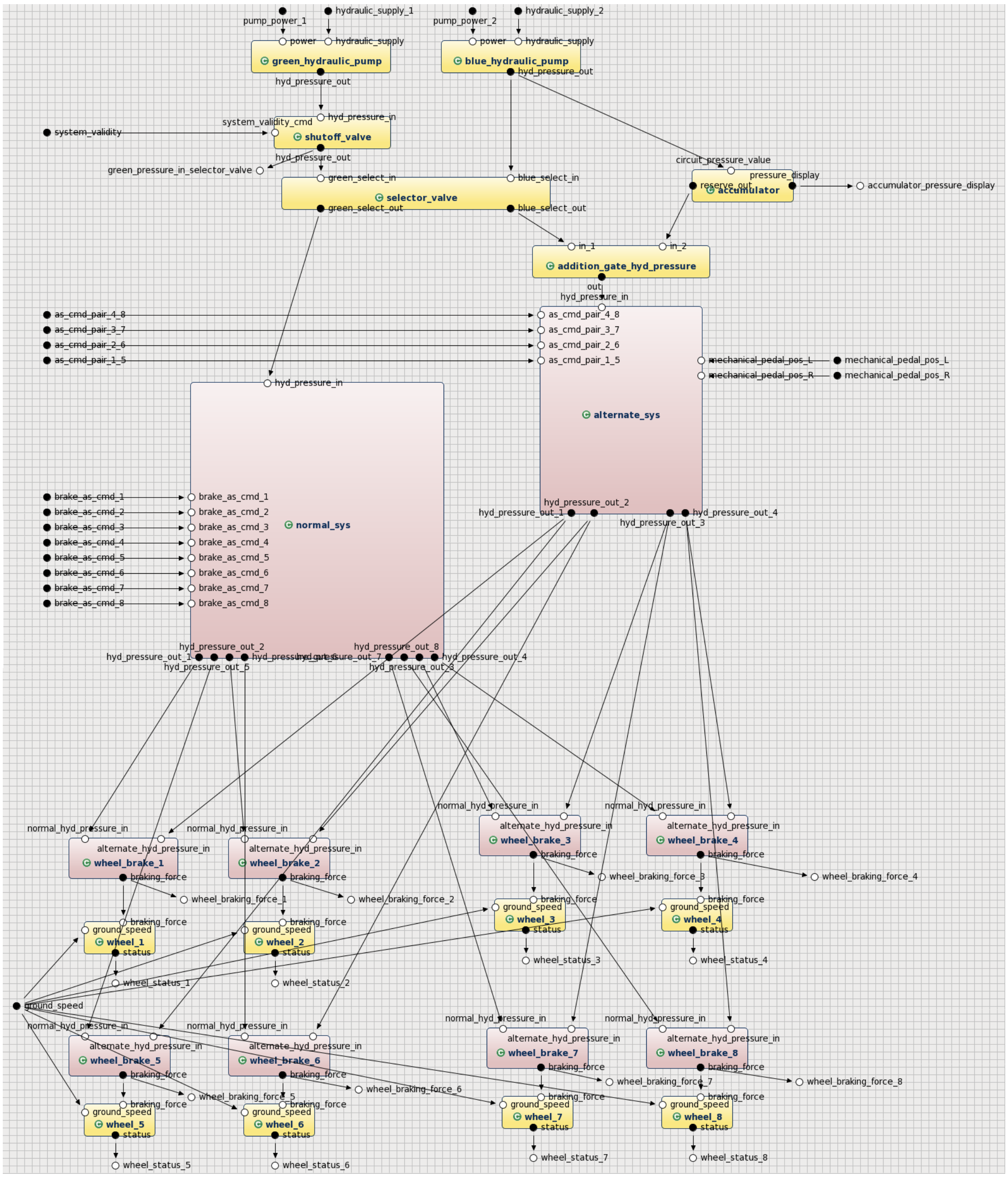


Figure 34: ARCH2 Physical system decomposition

### 4.4.3 Arch2bis

ARCH2BIS is an additional architecture which does not appear in the AIR6110. The goal is to show that a problem detected at the level of ARCH3 could have been detected at the level of ARCH2 and corrected with the same solutions that leads to ARCH4.

The problem detected (in which ARCH3 fails to guarantee mutual exclusion of Alternate and Normal Brake system operations) is due to the position of the accumulator in the blue circuit in the Physical system. As the Physical system is the same in ARCH2 the problem is also present there. By applying the modification introduced by ARCH4 in AIR6110 to ARCH2, we create ARCH2BIS: repositioning the Accumulator output before the Selector Valve. In this design the Accumulator should never release pressure into the Alternate Brake system if the

Normal Brake system is available. This implies that the operations of the two systems must be mutually exclusive. In addition, the Selector Valve is upgraded with an input coming from the Control system validity, the very same that the one that commands the Shutoff Valve. The behavior of the Selector Valve is then modified. The switch to the blue circuit is now triggered by a lack of pressure in the green circuit or the invalidity of the Control system.

The decomposition of Arch2bis closely parallels the decomposition of Arch2. The only modifications are the ones explained above. They are visible in Figure 35. An overview of the architecture model is available in Appendix D.

### 4.4.4 Arch3

Arch3 is an evolution of Arch2 based on a trade study of the BSCUs: the only difference on the two architectures is in the Control system, all the others features (upper level hierarchy, Physical system, sensors position, leaf component implementations) remain the same. The modeling is based on diagram shown in AIR6110 [25, p. 52, Fig. 28], and clarifications provided in Appendix A, Figure 38. An overview of the architecture modeling is available in Appendix E.

**Control system** The Control system of Arch3 is composed of a dual channel BSCU. The BSCU is decomposed into two channels and the gates that select commands between them. Each channel produces the eight brake anti-skid commands for the Normal Brake system and the four anti-skid commands for the Alternate Brake system. Each channel generates a validity command for the shutoff valve of the green circuit and validity status output information for the crew. Each channel takes as input its dedicated power source, the electrical pedal positions, the aircraft speed and the wheel status of each wheel.

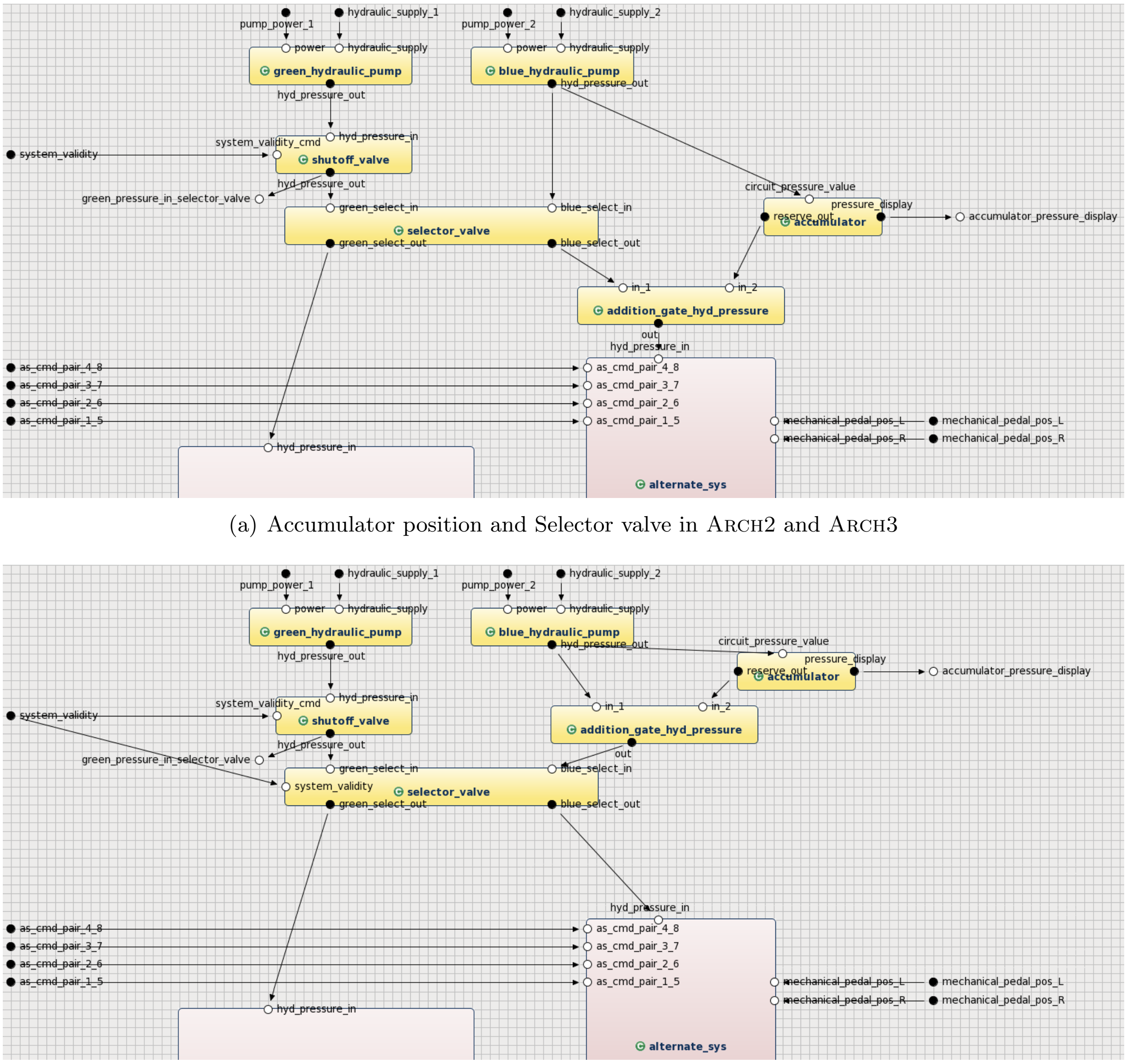
Each channel of the BSCU of Arch3 is similar to the structure of one BSCU of Arch2. A channel is divided into two sub-systems: a Monitor system and a Command system. The Monitor system is in charge of giving the status out, and thus the validity of the channel, depending on the power consumption and the correctness of the commands computed by the Command System. The Command system is in charge of creating brake and anti-skid commands. It is divided into four sub-systems, called Wheel Pair Command systems, one for each pair of wheels. These systems are in charge of creating the brake command and the anti-skid command for each pair of wheels.

The Wheel Pair Command system is decomposed into multiple leaf components, as follows:

- An Antiskid Command facility creates the antiskid command for each wheel, depending on the wheel status and the aircraft speed.
- A Brake Command facility creates the brake command depending on the pedal position.
- An Antiskid Command calculator creates antiskid commands for each pair of wheels in the Alternate Brake system. An Antiskid command is created if at least an anti-skid command is available for one wheel of the pair.
- Two Brake Command calculators create brake/antiskid commands for each wheel.

The switch between each channel commands is realized thanks to the Switch Gates as in Arch2: if channel 1 is valid, it is the commands of channel 1 that are sent to the Physical system. If channel 1 is invalid and channel 2 is valid, then the commands of channel 2 are sent to the the Physical system. If both channel are invalid, no command is sent.

An Or Gate is used to merge the two channels validity.



(a) Accumulator position and Selector valve in Arch2 and Arch3

(b) Accumulator position and Selector Valve in Arch2bis and Arch4

Figure 35: Modifications of the Physical system between Arch2 and Arch2bis, and between Arch3 and Arch4

**Physical system** Same as in Arch2.

**Sensors** Same as in Arch2.

**4.4.4.1 Diagram overview** An overview of the Control system and BSCU decomposition of Arch3 is given in Figure 36 and 37. A complete overview of the structure of each component of Arch3 are presented in Appendix E.

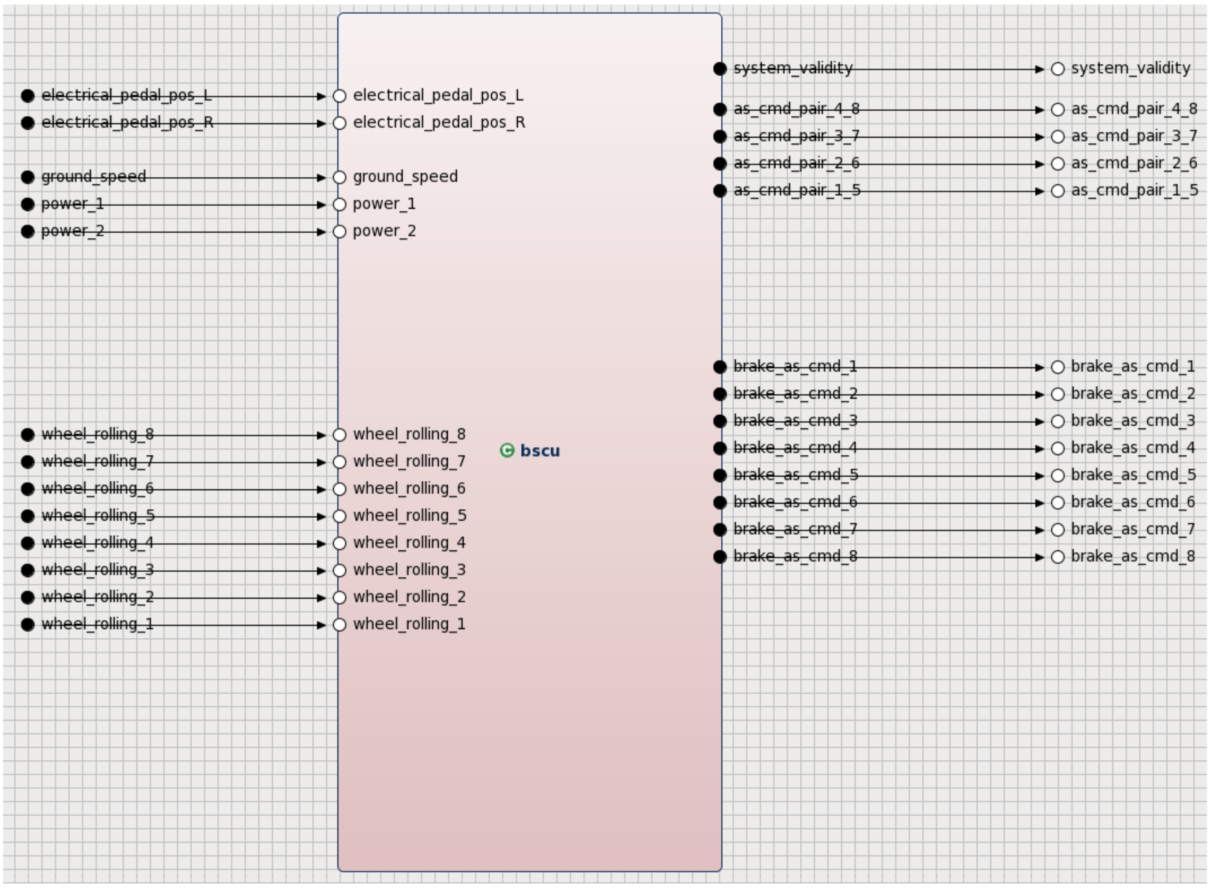


Figure 36: Arch3 Control system decomposition

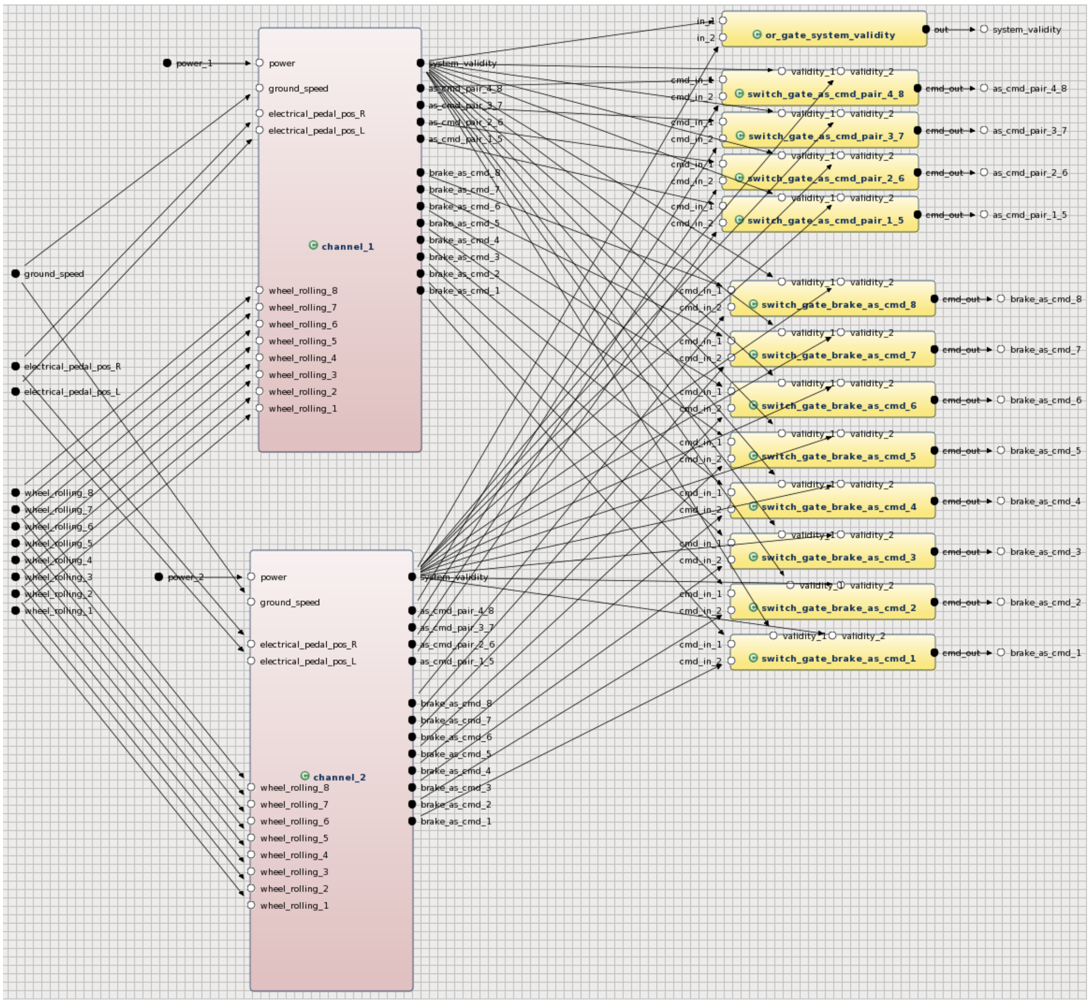


Figure 37: Arch3 BSCU decomposition

### 4.4.5 Arch4

As we explained previously, the problem detected in Arch3 about the position of the accumulator causes a failure to guarantee mutual exclusion of Alternate and Normal Brake system operations. This failure triggered the design ofArch4. The modifications applied are the repositioning of the accumulator upstream of the Selector Valve and an additional input from the Control System validity for the Selector Valve, as shown in AIR6110 [25, p. 68, Fig. 40]. In this design the operations of the Normal Brake system and the Alternate Brake system must be mutually exclusive. The modifications are visible in Figure 35.

All the other features are exactly the same as in Arch3. Arch4 represents the better architecture for the WBS. An overview of the architecture modeling is available in Appendix F.

## 4.5 Metrics about the architectures

Metrics about the architecture decomposition are given Table 1. Metrics about the system implementation are given in the left side of Table 2, where we report the number of state variables and the number of property instances available for the system implementation, based on the properties generated from the contracts for each component type. Metrics about the failure modes and the extended model of each architecture are given in the right side of Table 2.

Table 1: Architecture decomposition metrics

| Architecture | Total component types | Leaf component types | Total component instances | Leaf component instances | Max depth | Contracts |
|---|---|---|---|---|---|---|
| Arch1 | 22 | 15 | 100 | 79 | 5 | 121 |
| Arch2 | 29 | 20 | 168 | 143 | 5 | 129 |
| Arch2bis | 29 | 20 | 168 | 143 | 5 | 129 |
| Arch3 | 30 | 20 | 169 | 143 | 6 | 142 |
| Arch4 | 30 | 20 | 169 | 143 | 6 | 142 |

Table 2: System implementation metrics

| | | Sys. implementation | | Ext. Sys. implementation | | | |
|---|---|---|---|---|---|---|---|
| Architecture | Properties | State vars | | State vars | | Failure modes | fault vars |
| | | Bool | Enum | Bool | Enum | | |
| Arch1 | 199 | 31 | 55 | 74 | 184 | 28 | 170 |
| Arch2 | 291 | 79 | 88 | 156 | 311 | 33 | 261 |
| Arch2bis | 291 | 79 | 88 | 156 | 311 | 33 | 261 |
| Arch3 | 304 | 79 | 88 | 156 | 311 | 33 | 261 |
| Arch4 | 304 | 79 | 88 | 156 | 311 | 33 | 261 |

# 5 Analysis

In this section we present the results obtained from the different analyses making up our formal approach. In Section 5.1, we describe the results of the formal verification, going from the analysis of the architecture decomposition to the analysis of the monolithic model of each architecture. In Section 5.2, we present the result of the Fault Tree Analysis from the MBSA and we compare them with the results of the Fault Tree Analysis from the CBSA for each architecture. In Section 5.3, we compare the different architecture based on the results of the different analyses.

## 5.1 Formal verification

### 5.1.1 Summary

The formal verification is first applied via a contract-based approach within OCRA. The contract-based verification process is based on the following steps: the top level properties are stated as contracts in the form of temporal logic formulae at the system level; each component is associated with corresponding contracts; the correctness of each contract refinement is proved by means of temporal entailment checks; the SMV module associated with each leaf component is proved to correctly implement the corresponding contracts.

The same results are also obtained via a monolithic approach. The monolithic models, in form of SMV files, are analyzed with respect to properties resulting from the contracts in the architecture. We use nuXmv, running different verification engines: BDD-based model checking and IC3 [6].

All experiments are performed on a cluster of 64-bit Linux machines with 2.7 Ghz Intel Xeon X5650 CPU, using one core with a memory limit set to 10Gb. The results are reported in Table 3. The columns Ref. and Impl. represent time taken for the contract refinement and implementation checks. BDD-based model checking does not succeed in building the model. To run it, we simplify the monolithic model[6]. The simplification automatically removes redundant state variables exploiting functional dependencies among variables defined in the invariants. The execution time for this version of the model is tagged *'after simplification'* in the Table 3. We also apply IC3 engine on this simplified model. We observe that IC3 is the best engine to verify monolithic model. The difference between IC3 applied to the original monolithic model and IC3 applied to the simplified model can be explained by the fact that the simplification applied to the model, a relational one, is not adapted to IC3 algorithm.

The results show that the compositional approach is often faster than the monolithic analysis. Consider also that contract refinement and implementation checks are fully independent and localized, and can in principle be executed in parallel. For example, the VPar (Virtual Parallelization) column in Table 3 reports maximum computation time across various individual checks for the compositional approach, corresponding to the limit case where each check is run on a dedicated machine.

Aside from performance considerations, the most important result of the formal verification is that the analysis of some sanity checks pinpointed a problem with ARCH2 that is not reported in AIR6110. The problem is caused by the fact that the accumulator is positioned downstream of the selector valve, so that a fault in the accumulator can cause inadvertent braking. The problem is only reported for ARCH3; ARCH2BIS was included in the analysis to correct the problem. This result is described in detailed in 5.1.3.

| Arch | BDD (after simplification) | IC3 (after simplification) | IC3 | Ref. | Impl. | Tot. | VPar |
|---|---|---|---|---|---|---|---|
| ARCH1 | 38.32 | 53.30 | 56.62 | 1422.24 | 6.07 | 1428.31 | 439.62 |
| ARCH2 | 2700.64 | 599.02 | 153.28 | 102.04 | 1.26 | 103.30 | 24.12 |
| ARCH2BIS | 3069.82 | 628.09 | 153.19 | 32.38 | 1.26 | 33.64 | 1.39 |
| ARCH3 | 2935.88 | 671.29 | 159.01 | 72.87 | 1.29 | 74.16 | 10.74 |
| ARCH4 | 3429.59 | 652.50 | 158.51 | 29.74 | 1.29 | 31.03 | 1.78 |

Table 3: Results of the formal verifications (all the times are in seconds)

### 5.1.2 Arch1

All the checks terminate successfully. However, we can observe that the execution times for ARCH1 are really different than in the other architectures. ARCH1 is the most simple architecture, but also the less robust. The execution times of the monolithic analysis specifically reflect this: it is 3 time faster with IC3 engine in comparison of the other architectures. However, the execution time for the compositional approach is much worse. This may be explained by the fact that some of the contracts defined for ARCH1 are too strong or their refinement are too weak in comparison with the other architectures. More investigations are needed on this case in future work.

### 5.1.3 Arch2

All the checks terminate successfully. We can observe that the execution time for the compositional approach between ARCH2 and ARCH3 are in the same order.

Now we try to verify our assumption about the issue detected in ARCH3 about the position of the accumulator by strengthening some properties.

[6] NUXMV command `write_simplified_model_rel`

**Requirements addition: mutual exclusion of Alternate and Normal Brake system operations** In AIR6110, system requirements are defined for the Wheel Brake System. We chose to apply one of these requirements to the model. We apply the requirement S18-WBS-R-2973 *"Alternate system operations shall be precluded during Normal operation"*, extended with this property: *"Normal system operations shall be precluded during Alternate operation"*

This requirement is added in the contracts as follows: we add an assumption on the environment of each wheel brake and each brake actuator to the effect that it is never possible for hydraulic pressure supply from the Normal Brake system and from the Alternate Brake system at the same time. The representation in OCRA language is given in Listing 7. This assumption is then kept at the level of the monolithic model thanks to the automatic translation of the contracts into LTL properties during the generation of the system implementation from the architecture decomposition.

```
assume: always((normal_hyd_pressure_in>0 implies alternate_hyd_pressure_in=0)
               and (alternate_hyd_pressure_in>0 implies normal_hyd_pressure_in=0));
```

Listing 7: Assumption for the mutual exclusion of Alternate and Normal Brake system operations in OCRA contracts

The refinement check fails with the additional assumptions. The check takes 582.74 seconds and a problem is detected in the verification of the environment check of each wheel brake (i.e. the verification of the assumption), at the level of the Physical system. The time difference for the refinement check between the version of Arch2 with the assumptions and without is due to the check of additional assumes clauses. A counter-example generated for the wheel brake of the wheel 8 is given in Listing 8. We see, in the second state, that the wheel brake is supplied by the Normal Brake system and by the Alternate Brake system in this example (`normal_sys.hyd_pressure_out_8 = 1` and `alternate_sys.hyd_pressure_out_4 = 1`). We can also see that the system is in the Normal mode but the Alternate Brake system is supplied by the accumulator (the normal mode is deduced by `selector_valve.green_select_out = 1` and `selector_valve.blue_select_out = 0`, and `accumulator.reserve_out = 7` indicating accumulator supply). As an initial observation, we can guess the problem may originate from the position of the accumulator in the system, or the features of the accumulator used are not sufficient for the expected behavior of the WBS.

```
Checking the correct environment of "wheel_brake_8.supply_braking_force"...
-- as demonstrated by the following execution sequence
Trace Description: LTL Counterexample
Trace Type: Counterexample

  -- Loop starts here
  -> State Ports: 345.1 <-
    hydraulic_supply_1 = 1
    hydraulic_supply_2 = 1
    pump_power_1 = TRUE
    pump_power_2 = TRUE
    system_validity = TRUE
    brake_as_cmd_1 = FALSE
    brake_as_cmd_2 = FALSE
    brake_as_cmd_3 = FALSE
    brake_as_cmd_4 = FALSE
    brake_as_cmd_5 = FALSE
    brake_as_cmd_6 = FALSE
    brake_as_cmd_7 = FALSE
    brake_as_cmd_8 = TRUE
    as_cmd_pair_1_5 = FALSE
    as_cmd_pair_2_6 = FALSE
    as_cmd_pair_3_7 = FALSE
    as_cmd_pair_4_8 = FALSE
    ground_speed = 0
    mechanical_pedal_pos_L = FALSE
    mechanical_pedal_pos_R = FALSE
    wheel_8.status = stopped
    alternate_sys.hyd_pressure_out_1 = 0
    alternate_sys.hyd_pressure_out_2 = 0
    alternate_sys.hyd_pressure_out_3 = 0
    alternate_sys.hyd_pressure_out_4 = 0
    wheel_5.status = stopped
    wheel_2.status = stopped
    accumulator.reserve_out = 0
    accumulator.pressure_display = 0
    wheel_brake_8.braking_force = 0
    blue_hydraulic_pump.hyd_pressure_out = 1
    wheel_brake_5.braking_force = 0
    wheel_brake_2.braking_force = 0
    addition_gate_hyd_pressure.out = 0
    wheel_6.status = stopped
    normal_sys.hyd_pressure_out_1 = 0
    normal_sys.hyd_pressure_out_2 = 0
    normal_sys.hyd_pressure_out_3 = 0
    normal_sys.hyd_pressure_out_4 = 0
    normal_sys.hyd_pressure_out_5 = 0
    normal_sys.hyd_pressure_out_6 = 0
    normal_sys.hyd_pressure_out_7 = 0
    normal_sys.hyd_pressure_out_8 = 1
    wheel_3.status = stopped
    wheel_1.status = stopped
    shutoff_valve.hyd_pressure_out = 7
    wheel_brake_6.braking_force = 0
    green_hydraulic_pump.hyd_pressure_out = 7
    wheel_brake_3.braking_force = 0
    wheel_brake_1.braking_force = 0
    wheel_7.status = stopped
    wheel_4.status = stopped
    selector_valve.green_select_out = 1
    selector_valve.blue_select_out = 0
    wheel_brake_7.braking_force = 0
    wheel_brake_4.braking_force = 0

  -> State Ports: 345.2 <-
    hydraulic_supply_2 = 0
    mechanical_pedal_pos_R = TRUE
    alternate_sys.hyd_pressure_out_4 = 1
    accumulator.reserve_out = 7
    blue_hydraulic_pump.hyd_pressure_out = 0
    addition_gate_hyd_pressure.out = 7

  -- Loop starts here
  -> State Ports: 345.3 <-
    hydraulic_supply_2 = 1
    mechanical_pedal_pos_R = FALSE
    alternate_sys.hyd_pressure_out_4 = 0
    accumulator.reserve_out = 0
    blue_hydraulic_pump.hyd_pressure_out = 1
    addition_gate_hyd_pressure.out = 0

  -> State Ports: 345.4 <-

    [NOT OK]
```

Listing 8: counter example generated for the check of the correct environment of the wheel brake of the wheel 8

**Conclusion** We observe that the Alternate Brake system operations and the Normal Brake system operations are not mutually precluded in Arch2. The problem is the position of the accumulator in the architecture. Indeed, the accumulator is placed after the selector valve in the blue circuit and if the blue pump fails, the accumulator will release the reserve pressure in the

Alternate Brake system according to our model, even if the Normal Brake system is operating. Moreover, we can assume that even if the blue pump is still available, if the accumulator fails it can release pressure in the Alternate Brake system while the Normal Brake system is operating.

The problem of the position of the accumulator is detected in Arch3 in the AIR6110 document where it is the primary motivation for evoluting to Arch4. We proposed to apply the modification presented in Arch4 to Arch2 in order to obtain an intermediate architecture, and to verify the consequences of the modification. This leads to Arch2bis.

### 5.1.4 Arch2bis

All the checks terminate successfully. We can observe that the execution time for the compositional approach between Arch2bis and Arch4, as between Arch2 and Arch3, are in the same order.

The execution times given in Table 3 are the execution times without the additional assumptions in the properties for the wheel brakes. If we add the assumptions, all the checks are still True but the execution time is higher than the one in Table 3 and closer to the execution time for Arch2 with the assumptions.

These results make us confident about the solution developed on Arch4 for the position of the accumulator and its beneficial impact on the architecture.

### 5.1.5 Arch3

All the checks terminate successfully. We can observe that we have a similar execution time than Arch2 for the compositional approach.

### 5.1.6 Arch4

All the checks terminate successfully. We can also observe that we have a similar execution time as Arch2bis for the compositional approach.

## 5.2 Fault Tree Analysis

We now consider the construction of fault trees for each of the architectures and safety requirements, from the models obtained with the model extension functionality of xSAP, as described in Section 3.4. In order to cope with scalability issues, we limit the space of the problem in two ways: restricting the set of faults, and limiting the cardinality of the cut sets. This follows a standard practice in traditional safety analysis: given the manual effort required, priority is given to cut sets of lower cardinality or greater likelihood.

The analyses are run on the five architectures, for all the safety properties and two additional properties, under the assumption that the WBS environment never fails (always electrical power and always hydraulic supply to the WBS). We properties analyzed are:

- **S18-WBS-R-0321**: never loss of all wheel braking.
- **S18-WBS-R-0322-left**: never asymmetrical loss of wheel braking (left side).
- **S18-WBS-R-0322-right**: never asymmetrical loss of wheel braking (right side).
- **S18-WBS-R-0323**: never inadvertent braking of all wheels with all wheels locked (i.e. never inadvertent braking with all wheels locked).
- **S18-WBS-R-0324**: never inadvertent braking of all wheels.

- **S18-WBS-R-0325-wheel1**: never inadvertent braking of one wheel without locking.
- **S18-WBS-R-0325-wheel2**: same as the previous property but for wheel 2. We check the property of each wheel to ensure that each wheel behaves in the same way for the safety property.
- **S18-WBS-R-0325-wheel3**: same as the previous property but for wheel 3.
- **S18-WBS-R-0325-wheel4**: same as the previous property but for wheel 4.
- **S18-WBS-R-0325-wheel5**: same as the previous property but for wheel 5.
- **S18-WBS-R-0325-wheel6**: same as the previous property but for wheel 6.
- **S18-WBS-R-0325-wheel7**: same as the previous property but for wheel 7.
- **S18-WBS-R-0325-wheel8**: same as the previous property but for wheel 8.
- **Braking implies cmd w1**: This an additional property defined in the model to verify the expected behavior of the system. It allows checking, for each wheel, that if the system is braking, it means that the system has received a command from the pilot. Here we only take the property for the wheel 1 (w1) as a control sample.
- **Cmd implies braking w1**: This a second additional property defined in the model to verify the expected behavior of the system. It allows checking, for each wheel, that if the system received a command from the pilot, the system is braking. Here again, we only take the property for the wheel 1 (w1) as a control sample.

For each of these properties, their violation is used as Top Level Events (TLE) for the fault tree computations (in the following paragraphs, we will use the name of the properties to reference the TLE). For each TLE, cardinality goes from 1 to 5, and then to no restriction. In addition to the complete set of faults, six different restricted sets of faults are defined and observed:

- **Set1** The components that can have faults in this set are : Hydraulic Pump, Accumulator, Shutoff Valve, Selector Valve, Meter Valve, Antiskid Shutoff Valve.
- **Set2** The components that can have faults in this set are : Hydraulic Fuse, Hydraulic Piston, Brake Actuator, Wheel.
- **Set3** The components that can have faults in this set are : Brake Command Facility, Antiskid Command Facility, Normal Command Calculator, Alternate Command Calculator, Monitor System.
- **Set4** The components that can have faults in this set are : Switch Gate, Monitor System
- **Set5** The components that can have faults in this set are : Sensor, Sensor Pedal Position
- **Set6** The components that can have faults in this set are : Brake Command Facility, Antiskid Command Facility, Normal Command Calculator, Alternate Command Calculator, Meter Valve, AntiSkid Shutoff Valve

In total, 3150 fault tree constructions have been launched. Overall the activity resulted in 3089 computed fault trees and 61 computations timed out. The fault trees have minimal cut sets ranging from 0 to tens of thousands.

| Arch/Prop | | Prob. | $\lvert mcs\rvert = 1$ | $\lvert mcs\rvert = 2$ | $\lvert mcs\rvert = 3$ | $\lvert mcs\rvert = 4$ | $\lvert mcs\rvert = 5$ | Full |
|---|---|---|---|---|---|---|---|---|
| arch1 | S18-WBS-R-0321 | 1.45e-04 | 17 | 2 | 0 | 0 | 0 | N |
| | S18-WBS-R-0322-left | 1.45e-04 | 17 | 2 | 0 | 28561 | 0 | Y |
| | S18-WBS-R-0322-right | 1.45e-04 | 17 | 2 | 0 | 28561 | 0 | Y |
| | S18-WBS-R-0323 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | S18-WBS-R-0324 | 2.50e-11 | 0 | 1 | 0 | 0 | 8192 | N |
| | S18-WBS-R-0325-wheel1 | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel2 | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel3 | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel4 | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel5 | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel6 | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel7 | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel8 | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | braking_implies_cmd_w1 | 1.11e-04 | 13 | 1 | 0 | 0 | 0 | Y |
| | cmd_implies_braking_w1 | 2.57e-04 | 30 | 2 | 0 | 0 | 0 | Y |

Table 4: Fault trees results for arch1 for the full set of faults (- represents a timed out computation)

All fault tree constructions are performed using IC3 engine on a cluster of 64-bit Linux machines with CPU going from 2.4 Ghz to 2.7 Ghz Intel Xeon, with a memory limit set to 30Gb and a time limit of 10 hours (unless otherwise specified).

To ease the reading load, we only present in the following tables a sampling of the results: the results for the 15 chosen properties, for the full set of faults, with cardinality going from 1 to 5. An overview of all the results for each architecture are found in Appendix H, I, J, K and L. In these tables, we give the number of minimal cut sets for cardinality 1 to 5. For upper cardinality, we only indicates in the last column (Full) whether the computation has been completed (i.e. computed the minimal cut sets) without cardinality bound (Y) or if it timed out (N). We also report the probability (Prob.) for each of the TLE, for an association of the basic faults with a probability, as given in Section 4.2.3 (in the 'N' cases, the reported value is a lower bound). The execution time required to compute the fault tree for a given property ranges from seconds (for fault tree with dozens of minimal cut sets) to minutes or hours (for fault tree with thousands of minimal cut sets).

The problem has also been tackled by means of contract-based safety analysis [5]. Given the inherent scalability of the contract based approach, we are able to produce hierarchical fault trees (HFT) from the architecture decompositions and the contracts. The hierarchical fault trees are produced in a dozen minutes for all top level properties without any cardinality bounds or faults restrictions. An example is given in Appendix G. As discussed in [5], the compositional approach will produce hierarchical fault trees whose corresponding set of minimal cut sets is an over-approximation of the one obtained with the monolithic approach. This is confirmed in the experiments: for each property, we make a comparison of the minimal cuts sets obtained for the higher cardinality and for a full configurations of faults in the monolithic approach, with the minimal cut sets obtained from the contract based approach. We also notice that over-approximation is a common practice in safety analysis. The two approaches can be considered complementary.

### 5.2.1 Arch1

A sample of the results corresponding to the minimal cut sets (MCS) for each property at different cardinality for the full set of faults for the MBSA is given Table 4 and presented in the following paragraphs. The full results are given in Appendix H.

**S18-WBS-R-0321** At cardinality 1, there are 17 MCS. They correspond to the failure of each BSCU leaf component (8 antiskid command facility, 8 brake command facility and 1 monitor system). These MCS are surprising but they are highlighting an important problem in Arch1: the Control system is expected to cut the commands sent to the Physical system in case of failure. The failure of the Control system is achieved if at least one of its leaf component failed. In the case of Arch1, there is nothing that prevents the Control system to continue to sending commands to the Physical system if it is invalid. Specifically, if the Control system can continue to send commands, then it can apply anti-skid function when the WBS does not expect it. If we take the particular case where the Control system is invalid (because at least one of its leaf component fails) and the 8 wheels are skidding, the system expects to be able to brake without restriction. But if the Control system can still send commands even if invalid, it can still apply the anti-skid function for the 8 wheels and prevent the braking of the wheels because of their skidding. The system does not expect this behavior and sees it as a complete loss of wheel braking, triggered by the failure of at least one Control system leaf component.

At cardinality 2, there are 2 MCS that correspond to the loss of all the hydraulic pressure supplies, as expected: loss of the pump and loss of the accumulator or the shutoff valve fails closed and loss of the accumulator.

For cardinality 3 to 5, there is no MCS.

For the computation without restriction, the computation of the fault trees timed out.

The probability is about 1.45e-04 but the fault tree computation does not complete without restriction. It is not in agreement with the expected order for "extremely remote" (1.0e-7 or less) defined in [1]. Indeed, the single points of failure reflect an important problem of this architecture and dictate the probability value.

**S18-WBS-R-0322-left(right)** At cardinality 1, there are 17 MCS. They correspond to the failure of each BSCU leaf component (8 antiskid command facility, 8 brake command facility and 1 monitor system). As for the previous TLE, these MCS are surprising but they highlight the problem of the commands sent by an invalid Control system. In is case, the application of the anti-skid commands from the invalid Control system on one side when the system does not expect to receive commands can be interpreted as an asymmetrical loss of wheel braking.

The MCS of cardinality 2 are also surprising. Indeed they correspond to the loss of the pressure supply to the hydraulic system (pump fails or shutoff valve fails closed and the accumulator fails off) which can cause a full loss of wheel braking. The cause of these 2 MCS is due to our definition of the antiskid function and how we handle it in the top level property. For example, if one side is completely skidding and the other is supposed to brake, if we loss the pressure supply, we loose the capacity of braking on the side where we are supposed to brake, but as the other side is not supposed to brake due to the skidding of its wheels, there is no impact on it. This corner case must be further investigated in future work.

At cardinality 3, there is no MCS.

At cardinality 4, there are 28561 MCS. They correspond to the combinations of a component in failure in the hydraulic circuit part of each wheel of the specific side (meter valve fails, antiskid shutoff valve fails, hydraulic fuse fails, hydraulic piston fails, brake actuator fails and/or wheel sensor fails).

For cardinality 5 or above, there is no MCS. The computation of the fault trees without any restriction is completed.

The probability is about 1.45e-04 which does not achieve the required level of "extremely remote" (1.0e-7 or less) defined in [1]. The probability is dictated by the single points of failure which are, as in the previous TLE, due to an important issue in Arch1. But the original requirement required an additional loss of rudder or nose wheel steering with the current property, which means an additional component in fault that is not represented in our model. The exact impact of this additional fault on the probability is unknown, and would require modeling of other systems external to the WBS.

**S18-WBS-R-0323** The fault tree computation does not complete without restriction and there is no minimal cut set up to cardinality 5 for the full set of faults.

As the fault tree computation does not terminate without restriction and there is no minimal cut set up to cardinality 5 for the full set of faults, the lower bound of the probability is 0 for this TLE. But we can assume, based on the probability order of the failure modes of each component, that the probability for the minimal cut sets with a cardinality greater than 5 will be much lower than the expected order ("extremely remote", 1.0e-7 or less).

**S18-WBS-R-0324** The lower cardinality of the MCS obtained is 2 with only one MCS, which corresponds to the combination of the two pedal position sensors sending erroneous commands (For example, sending an electrical signal when there is none).

There is no MCS at cardinality 3 and 4. At cardinality 5, there are more than 8192 MCS. They are combinations of one pedal position sensor of one side (left for example) sending erroneous command, with a component in failure in the hydraulic circuit (meter valve or hydraulic piston or brake actuator) of each of the four wheels in the other side (right for example), or the brake command facility of each of these four wheels.

For cardinality greater than 5, the computation of the fault trees is timed out.

The probability is about 2.50e-11 but here again the fault tree computation does not complete without restriction. However, the computed probability is in agreement with the expected order for "extremely improbable" (1.0e-9 or less).

**S18-WBS-R-0325-wheelX** The lower cardinality of the MCS obtained is 1. At this cardinality, there are 9 MCS: 3 about the meter valve (failed open, failed last position or failed random position), 2 about the brake actuator (failed open or failed at the last position), 2 about the hydraulic piston (failed open or failed at the last position), 1 about the pedal position sensor sending an erroneous command and 1 about the brake command facility sending erroneous command. Except the brake command facility failure, all the MCS make sense: they correspond to a failure of a component in the hydraulic circuit leading to the inadvertent braking of the wheel. The presence of the failure of the brake command facility is due to the issue of the Control system which is able to send erroneous command even if invalid.

For cardinality 2 or above, there is no MCS. The computation of the fault trees terminated without restriction.

The probability is about 9.63e-05. It is not in agreement with the expected order for "extremely improbable" (1.0e-9 or less) defined in [1]. Apart from the problem of the MCS due to an issue in ARCH1, the safety requirement used as TLE specified an "undetected" inadvertent braking. This aspect is not taking into account in our modeling which means that it should need another component to be in fault to cause the violation of the safety requirement. In this case, the probability should be lower than the one obtained.

**Braking implies cmd w1** The lower cardinality of the MCS obtained is 1. At this cardinality, there are 13 MCS: 3 about the meter valve (failed open, failed last position or failed random position), 3 about the antiskid shutoff valve (failed open, failed last position or failed random position), 2 about the brake actuator (failed open or failed at the last position), 2 about the hydraulic piston (failed open or failed at the last position), 1 for the pedal position sensor sending an erroneous command and 1 for the brake command facility sending erroneous commands. Same as before: except the brake command facility failure, all the MCS make sense.

At cardinality 2, there is 1 MCS corresponding to the monitor system and the antiskid command facility of the wheel sending erroneous commands. In this specific case, the antiskid command facility of the wheel will send erroneous command and the monitor system will not detect it, letting the system think that everything is ok. The antiskid command will not be produced and the wheel which was not supposed to brake due to the antiskid command will brake.

For cardinality 3 or above, there is no MCS. The computation of the fault trees terminates without restriction. The probability is about 1.11e-04. We do not have any reference to compare with.

**Cmd implies braking w1** At cardinality 1, there are 30 MCS: the failure of each BSCU leaf component (8 antiskid command facility, 8 brake command facility and 1 monitor system), 3 about the meter valve (failed closed, failed last position or failed random position), 3 about the antiskid shutoff valve (failed closed, failed last position or failed random position), 2 about the brake actuator (failed closed or failed at the last position), 2 about the hydraulic piston (failed closed or failed at the last position), 2 about the wheel sensor (failed no data or erroneous data) and one about the hydraulic fuse failed closed. Despite of the 17 MCS on the BSCU leaf component due to the issue of Arch1, the other computed MCS make sense.

At cardinality 2, there are 2 MCS that correspond to the loss of all the hydraulic pressure supply: loss of the pump and loss of the accumulator or the shutoff valve fails closed and loss of the accumulator.

For cardinality 3 to 5, there is no MCS. The computation terminates without restriction. The probability is about 2.57e-04. We do not have any reference to compare with.

**Summary and CBSA comparison** The reviewed MCS pinpoints an important issue in Arch1: the Control system (BSCU) do not cut off the sending of commands if it is invalid. Due to the single points of failure resulting from this issue, the probability for some of the TLE are too high(S18-WBS-R-0321,S18-WBS-R-0322).

The hierarchical fault tree generated from CBSA for each of the TLE have been confirmed to be an over-approximation of the fault trees generated by the MBSA. But the particular case of the property S18-WBS-R-0323, where there is no MCS computed for the full set of faults, does not allow us to state anything about the result of this comparison for this property.

### 5.2.2 Arch2

A sample of the results corresponding to the minimal cut sets (MCS) for each property at different cardinality for the full set of faults for the MBSA is given Table 5 and described in the following paragraphs. The full results are given in Appendix I.

**S18-WBS-R-0321** The lower cardinality of the MCS obtained is 2. There are 6 MCS at this cardinality that are combinations of failures of the two pedal position sensors (4 of the MCS), and the failure of the selector valve in the last position associated to a failure causing the loss of pressure in the green circuit (loss of the green hydraulic pump or the shutoff valve fails closed). They make sense: if the two pedal position sensors fails at the same time to transform the mechanical position in an electrical signal, a loss of all wheel braking can happen; and if the selector valve is stuck in the Normal Brake system and no pressure is coming in, the braking will be impossible.

| Arch/Prop | | Prob. | $\vert mcs\vert = 1$ | $\vert mcs\vert = 2$ | $\vert mcs\vert = 3$ | $\vert mcs\vert = 4$ | $\vert mcs\vert = 5$ | Full |
|---|---|---|---|---|---|---|---|---|
| arch2 | S18-WBS-R-0321 | 4.51e-10 | 0 | 6 | 1252 | 629 | - | N |
| | S18-WBS-R-0322-left | 1.00e-05 | 2 | 2 | 732 | 47583 | - | N |
| | S18-WBS-R-0322-right | 1.00e-05 | 2 | 2 | 732 | 47583 | - | N |
| | S18-WBS-R-0323 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | S18-WBS-R-0324 | 2.50e-11 | 0 | 1 | 0 | 38 | 10859 | N |
| | S18-WBS-R-0325-wheel1 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel2 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel3 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel4 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel5 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel6 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel7 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel8 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | braking_implies_cmd_w1 | 1.25e-04 | 10 | 40 | 2651 | 7395 | 9636 | Y |
| | cmd_implies_braking_w1 | 1.13e-04 | 13 | 30 | 8053 | 3815 | 2873 | Y |

Table 5: Fault trees results for arch2 for the full set of faults (- represents a timed out computation)

For cardinality 3, there are more than 1000 MCS. They are composed of the combination of the loss of all the hydraulic supply (loss of the two pumps and the accumulator, or the shutoff valve fails closed and loss of the blue pump and the accumulator) and mainly two other kind of MCS: one component of each BSCU fails (causing the validity of the Control system to be false and the shutoff valve cutting the pressure going to the Normal Brake system) and the selector salve fails at last position, causing the WBS to be stuck in the Normal mode with no pressure; Or one component of each BSCU fails (Control system invalid) and the shutoff valve fails open, causing the WBS to be stuck in the Normal Brake system, but without any commands sent by the Control system.

For cardinality 4, there are approximately 600 MCS. They are mainly combinations of failure of one component of each BSCU causing the WBS to go to the Alternate Brake system, and a loss of the blue pump and the accumulator, causing the WBS to be in the Alternate Brake system without pressure supply.

For cardinality 5 and above, the computation of the fault trees is timed out.

The probability is about 4.51e-10 but the fault tree computation does not terminate without restriction. Nevertheless, the probability is in agreement with the expected order for "extremely remote" (1.0e-7 or less) but it is lower than the minimum bound (1.0e-9) defined in [1].

**S18-WBS-R-0322-left(right)** The lower cardinality of the MCS obtained is 1. The single points of failure are the 2 failure modes of the pedal position sensor (no date or erroneous data) of the side of the property (left or right). Indeed, if only one of the pedal position sensor fails to convert the signal for the Control system, it can cause an asymmetrical loss of wheel braking on the side of the pedal.

The MCS of cardinality 2 are more surprising. Indeed they correspond to the loss of the supply of the Normal Brake system (loss of the green pump of shutoff valve failed closed ) and the selector valve that fails stuck at this position, which can cause a full loss of wheel braking. The presence of these 2 MCS can be due to our definition of the antiskid function and how we handle it in our property. For example, if one side is completely skidding and the other is supposed to brake, and in addition the pressure supply is lost without being able to change circuit, the capacity of braking on the side where we are supposed to brake is lost, but as the other side is not supposed to brake due to the skidding of its wheels, there is no impact on it, causing an asymmetrical loss of wheel braking. This corner case must be investigated in future work.

For cardinality 3, there are about 700 MCS. They correspond to different combinations: loss of the pressure in the green circuit, causing the system going to the Alternate Brake system, and the loss of two components of the specific side causing the loss of the wheel braking (all possible combinations of loss of two wheel sensors, loss of two alternate meter valves or loss of two antiskid shutoff valves or combination of each one of them). Indeed, as the braking of the wheels is managed by pair in the Alternate Brake system, a failure of one component of the hydraulic circuit of the sensor for each pair is sufficient to loose the braking on the four wheels. In addition, the other MCS are mainly combinations of one component of each BSCU failed (Control System invalid) and the shutoff salve fails open, causing the WBS to be stuck in the Normal Brake system, but without any command sent by the Control system. There are also combinations causing the full loss of pressure supply. In these cases, the same impact of the anti-skid function as in the MCS of cardinality 2 is observed.

For cardinality 4, there are dozens of thousands of MCS. There are mainly composed of two combinations of faults: first, one component of each BSCU failed causing the system to be in the Alternate Brake system and the loss of two components of the specific side causing the loss of the wheel braking ; second, the failure of a component in the hydraulic circuit or in the command chain of the braking of each wheel in the specific side. We also observe MCS composed of combinations of failures of BSCU components where, one component of BSCU 1 is in fault, causing the BSCU 1 to be invalid, with two components responsible for the brake commands creation of the wheels in BSCU 2 for the specific side in faults plus the monitor system of BSCU 2 failing to detect the failures.

For cardinality 5 and above, the computation of the fault trees is timed out.

The probability is about 1.00e-05 but the fault tree computation does not terminate without restriction. The probability order is higher than the one expected for “extremely remote” (1.0e-7 or less). It may be explained because the original requirement required an additional loss of rudder or nose wheel steering with the current property, which means an additional component in fault that is not represented in our model. In this way, we should have no single point of failure (MCS of cardinality 1) and a lower probability.

For this TLE, the results for the left side and the right side are the same.

**S18-WBS-R-0323** The fault tree computation does not complete without restriction and there are no minimal cut sets up to cardinality 5 for the full set of faults. However, we observe that by restricting the set of faults, the fault tree computation can terminate without bound on the cardinality. For example, for the set6, we are able to find dozen of thousands MCS from cardinality 6. One of the possible combination of faults is one component of each BSCU failed causing the WBS to be in the Alternate mode without anti-skid function, and the 4 meter valves of the Alternate Brake system failed open.

As the fault tree computation does not complete without restriction and there are no minimal cut sets up to cardinality 5 for the full set of faults, the lowest bound of the probability is 0 for this TLE. But we can assume, based on the probability order of the failure modes of each component, that the probability for the minimal cut sets with a cardinality greater than 5 will be much lower than the expected order (“extremely remote”, 1.0e-7 or less).

**S18-WBS-R-0324** The lower cardinality of the MCS obtained is 2 only one MCS, which corresponds to the combination of the two pedal position sensors sending erroneous commands (For example, sending an electrical signal when pedals are not depressed).

There is no MCS at cardinality 3.

At cardinality 4, there are 38 MCS. Two of them correspond to the combination of one pedal position sensor of one side (left for example) sending wrong command, in addition of three failures in the Control system: The monitor system of BSCU 1 is sending a wrong validity signal and the brake commands computed by the brake command facility of BSCU 1 for each pair of wheels of the other side (right for example) sent wrong command too. The other MCS are more interesting. They are highlighting the wrong position of the accumulator: they are combination of the accumulator failed opened or the blue pump failed off, as the WBS is still in the Normal mode, with one pedal position sensor of one side (left for example) sending wrong command and the two alternate meter valves of the other side failed opened.

At cardinality 5, there are more than 10000 MCS. They are mainly combinations of one pedal position sensor of one side (left for example) sending erroneous command, with a component in failure in the green hydraulic circuit of each of the four wheels of the other side (right for example). There are also, for example, combinations of the loss of the green hydraulic pump, causing the WBS to be in the Alternate mode, with a failure of the meter valve of each pair of wheel. There is also a specific MCS composed of the failure of the monitor system of the BSCU 1 plus the failure of the four brake command facility of BSCU 1 responsible for the creation of the brake commands for all the wheels. Finally, we can observe combinations due the wrong position of the accumulator.

For cardinality greater than 5, the computation of the fault trees is timed out.

The probability is about 2.50e-11 but the fault tree computation does not complete without restriction. However, the computed probability is in agreement with the expected order for “extremely improbable” (1.0e-9 or less).

**S18-WBS-R-0325-wheelX** The lower cardinality of the MCS obtained is 1. There are 9 MCS for this cardinality: 3 about the meter valve of the Normal Brake system (failed open, failed last position or failed random position), 2 about the brake actuator (failed open or failed at the last position), 2 about the normal hydraulic piston (failed open or failed at the last position), 1 for the pedal position sensor sending an erroneous command and finally 1 for the alternate hydraulic piston failed open. However, the safety requirement specified an “undetected” inadvertent braking. This aspect is not taken into account in our modeling (no detection of the braking force) which means that it would need another component to be in fault to cause the violation of the safety requirement, so at least MCS of cardinality 2.

At cardinality 2, we have 19 MCS. 7 of them are due to the wrong position of the accumulator and are a combination of the loss of the blue hydraulic pump or the accumulator failed open with a failure of the alternate meter valve or alternate hydraulic piston of the specific wheel. The others are combinations of the loss of the pressure in the green circuit (loss of the green pump or shutoff valve fails closed) with a failure of the alternate meter valve or alternate hydraulic piston. The last ones are combination of failure of the Control system components: the component responsible of the creation of the braking command for the normal system for the BSCU 1 with a failure of the monitor system or the corresponding switch gate, causing the Control system to keep sending the braking command of the BSCU 1 for the specific wheel.

At cardinality 3, we have more than 2597 MCS. There are mainly a combination of one component of each BSCU failed causing the WBS to be in the Alternate Brake system and the failure of the meter valve or the hydraulic piston of the Alternate Brake system attached to the specific wheel. There are also some combinations about failures of Control system components like one of the components of BSCU 1 failed, leading to the use of BSCU 2, plus the failure of one of the components in BSCU 2 responsible for the creation of the brake command for the specific wheel and the monitor system of BSCU 2 failing to detect the error.

For cardinality 4 and above, there is no MCS. The computation of the fault tree finished without restriction.

The probability is about 1.20e-04 which is more than the one expected by the safety requirement. The failure conditions should be extremely improbable, which means with a probability of 1.0e-9 or less. But the safety requirement specified an “undetected” inadvertent braking. As we said previously, this aspect is not taken into account in our model (no detection of the braking force) which means that it should need another component to be in fault to cause the violation of the safety requirement. As a result, the probability should be lower than the one obtained. So we are still confident of the computed probability for the version of the safety requirement used.

For this TLE, the results for the 8 wheels are the same.

**Braking implies cmd w1** For this TLE, there are 10 MCS of cardinality: 3 about the meter valve of the Normal Brake system (failed open, failed last position or failed random position), 2 about the brake actuator (failed open or failed at the last position), 2 about the normal hydraulic piston (failed open or failed at the last position), 1 about the pedal position sensor sending an erroneous command, 1 about the alternate hydraulic piston failed open and 1 about the sensor of the wheel sending erroneous data.

For cardinality 2, there are 40 MCS. They are mainly combinations of a failure leading to the Alternate mode (Loss of the green pump or shutoff valve failed closed) with a failure of a component having an impact on the braking of the wheel in the Alternate Brake system (alternate meter valve, alternate antiskid shutoff valve, alternate hydraulic piston, sensor of the pair of the wheel,...). There are also combinations about the failure of one of the BSCU 1 component responsible for the commands creation of the wheel plus the switch gate corresponding to the command failed at last position (BSCU 1) or the monitor system of the BSCU 1 missing to detect the wrong command creation. In addition we have 16 minimal cut sets linked to the wrong position of the accumulator: loss of of the blue pump or accumulator failed open with with a failure of a component having an impact on the braking of the wheel in the Alternate Brake system.

At cardinality 3, we observe 2651 MCS. They are mainly combinations of one component of each BSCU failed, causing the WBS to be in the Alternate Brake system, and the failure of the meter valve or the hydraulic piston of the Alternate Brake system attached to the specific wheel. We can also see 4 MCS due to the wrong position of the accumulator: the blue pump failed off or accumulator failed open, plus the failure of a component responsible for the creation of the alternate commands in the BSCU 1 for the specific wheel, and a failure of the switch gate linked to this command or failure of the monitor system to detect the erroneous command creation.

At cardinality 4 and 5, there are thousands of MCS. We can observe a lot of MCS due to the wrong position of the accumulator.

The fault tree computation terminates without restriction and generates MCS up to cardinality 8.

Concerning the probability, we do not have reference for this property but we can see that its is of the same order than the probability about the inadvertent braking of one wheel without locking (S18-WBS-R-0325-wheelX).

**Cmd implies braking w1** There are 13 MCS of cardinality 1: 3 about the meter valve of the Normal Brake system (failed closed, failed last position or failed random position), 2 about the brake actuator (failed full off or failed at the last position), 2 about the Normal hydraulic piston (failed full off or failed at the last position), 2 about the pedal position sensor sending an erroneous command or no data, 2 about the wheel sensor sending erroneous data or no data, 1 about the normal hydraulic fuse failed closed and 1 about the switch gate responsible for the brake command of the wheel in the Normal mode failing at an intermediate position (no command sent).

At cardinality 2, the 30 MCS are mainly combinations of a failure leading to the Alternate mode (Loss of the green pump or shutoff valve failed closed) with a failure of a component having an impact on the braking of the wheel in the Alternate Brake system (alternate meter valve, alternate antiskid shutoff valve, alternate hydraulic piston, sensor of the pair of the wheel, ...). There are also combinations about the failure of one of the BSCU component responsible for the commands creation of the pair of the wheel with the switch gate corresponding to the command failed at last position (BSCU 1) or the monitor system of the BSCU 1 missing to detect the wrong command creation.

For cardinality 3, there are thousands of MCS. They are mainly combinations that can lead the WBS to be stuck in the Normal Brake system without commands or without pressure supply (one component of each BSCU failed with the shutoff valve failed open or the selector valve failed last position), or failures leading to the Alternate Brake system (one component of each BSCU failed) with failure of one component of it causing the loss of wheel braking for the specific wheel (valve failed closed, piston or brake actuator failed full off, fuse failed closed, ...).

For cardinality 4 to 5, there are thousands of MCS which are mainly combinations composed of failure of Control system component, with some of them associated to a component of the Alternate Brake system for the specific wheel. Here too we can observe MCS due to the wrong position of the accumulator.

The fault tree computation terminates without restriction and generates MCS up to cardinality 6.

Concerning the probability, it is about 1.13e-04 but we do not have any reference for this property.

**Summary and CBSA comparison** The reviewed MCS make sense and the computed probabilities are approximately of a close order of the one required by the requirements, assuming the part of the requirement we abstracted. One unexpected case is that we have MCS for the TLE about the asymmetrical loss of wheel braking(S18-WBS-R-0322-left(right)) that correspond to a complete loss of hydraulic pressure or a complete loss of commands. As we explained, they may be due to our definition of the antiskid function and how we handle it in the property. It will need a deeper investigation in future work. More interesting, the wrong position of the accumulator is detected during the analysis and produced additional MCS for some TLEs.

The hierarchical fault tree generated from CBSA for each of the TLE have been confirmed to be an over-approximation of the fault trees generated by the MBSA. But the particular case of the property S18-WBS-R-0323, where there is not MCS computed for the full set of faults, does not allow us to state anything about the result of this comparison for this property.

### 5.2.3 Arch2bis

A sample of the results corresponding to the minimal cut sets (MCS) for each property at different cardinality for the full set of faults for the MBSA is given Table 6 and described in the following paragraphs. The full results are given in Appendix J.

**S18-WBS-R-0321** The lowest cardinality MCS is 2, as in Arch2. There are 6 MCS at this cardinality: the combination of the two pedal position sensors failures (4 of the MCS), and the failure of the selector valve in the last position associated to a failure causing the loss of pressure in the green circuit (loss of the green hydraulic pump or the shutoff valve failed closed).

| Arch/Prop | | Prob. | $\|mcs\| = 1$ | $\|mcs\| = 2$ | $\|mcs\| = 3$ | $\|mcs\| = 4$ | $\|mcs\| = 5$ | Full |
|---|---|---|---|---|---|---|---|---|
| arch2bis | S18-WBS-R-0321 | 4.51e-10 | 0 | 6 | 627 | 629 | - | N |
| | S18-WBS-R-0322-left | 1.00e-05 | 2 | 2 | 203 | 46287 | - | N |
| | S18-WBS-R-0322-right | 1.00e-05 | 2 | 2 | 203 | 46287 | - | N |
| | S18-WBS-R-0323 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | S18-WBS-R-0324 | 2.50e-11 | 0 | 1 | 0 | 2 | 8729 | N |
| | S18-WBS-R-0325-wheel1 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel2 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel3 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel4 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel5 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel6 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel7 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel8 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | braking_implies_cmd_w1 | 1.25e-04 | 10 | 24 | 2647 | 4530 | 59 | Y |
| | cmd_implies_braking_w1 | 1.13e-04 | 13 | 30 | 7428 | 3815 | 1768 | Y |

Table 6: Fault trees results for arch2bis for the full set of faults (- represents a timed out computation)

For cardinality 3, there are 627 MCS. they are composed of the loss of all the hydraulic supply (Loss of the two pumps and the accumulator, or the shutoff valve fails closed and loss of the blue pump and the accumulator) and mainly MCS with combinations of the form: one component of each BSCU failed (causing the validity of the Control system to be false and the shutoff valve cutting the pressure going to the Normal Brake system) and the selector valve fails at last position causing the WBS to be stuck in the Normal mode with no pressure. We do not have the combinations of one component of each BSCU failed (Control System invalid) and the shutoff valve fails open as in Arch2, due to the modification of the selector valve in Arch2bis. Indeed, the additional input from the Control system validity for the selector valve prevents the MCS implying the shutoff valve failed open at this cardinality.

For cardinality 4, there are approximately 600 MCS, as in Arch2. They are mainly combinations of failure of one component of each BSCU failed causing the WBS to go to the Alternate Brake system, and a loss of the blue pump and the accumulator, causing the WBS to be in the Alternate Brake system without pressure supply.

For cardinality 5 and above for the full set of faults, the computation of the fault trees times out.

The probability is about 4.51e-10 but the fault tree computation does not complete without restriction. Nevertheless, the probability is in agreement with the expected order for "extremely remote" (1.0e-7 or less) but we are lower than the minimum bound (1.0e-9) defined in [1].

**S18-WBS-R-0322-left(right)** The lower cardinality of the MCS obtained is 1. The single points of failure are the 2 failure modes of the pedal position sensor of the side of the property (left or right), as in Arch2. Indeed, if only one of the pedal position sensor fails to convert the signal for the Control system, it can cause an asymmetrical loss of wheel braking on the side of the pedal.

The MCS of cardinality 2 correspond to the loss of the supply of the Normal Brake system and the selector valve that fails stuck at this position, which can cause a full loss of wheel braking. As in Arch2, the presence of these 2 MCS can be due to our definition of our antiskid function and how we handle it in our property. This corner case must be investigated in future work.

For cardinality 3, there are 203 MCS, which is less than in Arch2. They correspond to different combinations: loss of the pressure in the green circuit, causing the system going to the Alternate Brake system, plus the loss of two components of the specific side causing the loss of the wheel braking (all possible combinations of loss of two wheel sensors, loss of two meter valves or loss of two antiskid shutoff valves or combination of each one of them).There are also combinations causing the full loss of pressure supply. In this case, the same impact of the anti-skid function as in the MCS of cardinality 2 is observed. In comparison with Arch2, the MCS implying the shutoff valve failed open are not present anymore.

For cardinality 4, there are dozens of thousands of MCS. There are mainly composed of two combinations of faults: first, one component of each BSCU failed causing the system to be in the Alternate Brake system plus the loss of two components of the wheel pairs of the specific side causing the loss of the wheel braking ; second, the failure of a component in the hydraulic circuit or in the command chain for the braking of each of the four wheels of the specific side. We also observe MCS composed of combinations of failures of BSCU components where, one component of BSCU 1 is in fault, causing the BSCU 1 to be invalid, with two components responsible for the brake commands creation of the wheels in BSCU 2 for the specific side in faults plus the monitor system of BSCU 2 failing to detect the failures. There are less MCS than in Arch2 (around 1200 less) due to the additional input from the Control system validity to the selector valve that prevents the MCS including the shutoff valve failed open.

For cardinality 5 and above, the computation of the fault trees is timed out.

The probability is about 1.00e-05 but the fault tree computation does not complete without restriction. The probability order is higher than the one expected for "extremely remote" (1.0e-7 or less). It may be explained because the original requirement required an additional loss of rudder or nose wheel steering with the current property, which means an additional component in fault that is not represented in our model. In this way, we should not have single point of failure (MCS of cardinality 1) but we should have a lower probability.

The results are the same for the properties applied on each side.

**S18-WBS-R-0323** As in Arch2, the fault tree computation does not terminate without restriction and there is no MCS up to cardinality 5 for the full set of faults. However, we can see that by restricting the set of faults, we are able to terminate the fault tree computation without bound on the cardinality. For example, as in Arch2, for the set6, we are able to find dozen of thousands of MCS from cardinality 6.

The fault tree computation does not complete without restriction and there is no MCS up to cardinality 5. We can assume, based on the probability order of the failure modes of each component, that the probability for the MCS with a cardinality greater than 5 will be much more lower than the expected order ("extremely remote", 1.0e-7 or less).

**S18-WBS-R-0324** The lower cardinality of the MCS obtained is 2: there is one MCS which corresponds to the combination of the two pedal position sensors sending erroneous commands.

There is no MCS at cardinality 3.

At cardinality 4, there are 2 MCS. They correspond to the combinations of one pedal position sensor of one side (left for example) sending wrong command, in addition of three failures in the Control system: The monitor system of BSCU 1 is sending a wrong validity signal and the brake commands computed by the brake command facility of each pair of wheels of the other side (right for example) sent wrong command too. In comparison of Arch2, the 36 MCS due to the wrong position of the accumulator are removed thanks to the correction applied in Arch2bis.

At cardinality 5, there are around 8000 MCS, less than in Arch2. They are mainly combinations of one pedal position sensor of one side (left for example) sending wrong command, with a component in failure for each of the four wheels of the other side (right for example) in the green hydraulic circuit. There are also combinations of the loss of the green hydraulic pump, causing the WBS to be in the Alternate mode, with a failure of the meter valve of each pair of wheels. There is also a specific MCS composed of the failure of the monitor system of the BSCU 1 plus the failure of the four brake command facility of BSCU 1 responsible for the creation of the brake commands for all the wheels. Same as previously, the difference with the MCS of Arch2 can be explained by the correction of the position of the accumulator.

For cardinality greater than 5, the computation of the fault trees is timed out.

The probability is about 2.50e-11 but the fault tree computation does not terminate without restriction. However, the computed probability is in agreement with the expected order for “extremely improbable” (1.0e-9 or less).

**S18-WBS-R-0325-wheelX** The lower cardinality of the MCS obtained is 1 for the full set of faults. There are 9 MCS for this cardinality: 3 about the meter valve of the Normal Brake system (failed open, failed last position or failed random position), 2 about the brake actuator (failed open or failed at the last position), 2 about the normal hydraulic piston (failed open or failed at the last position), 1 for the pedal position sensor sending an erroneous command and 1 for the alternate hydraulic piston failed open. However, the safety requirement specified an “undetected” inadvertent braking. This aspect is not taken into account in our modeling (no detection of the braking or not) which means that it will require another component to be in fault to cause the violation of the safety requirement, so no single points of failure and at minimum MCS of cardinality 2.

At cardinality 2, we have 12 MCS. They are combinations of the loss of the pressure in the green circuit (loss of the green pump or shutoff valve fails closed) with a failure of the alternate meter valve or alternate hydraulic piston. The others are combinations of failure of the Control system components: failure of the component responsible of the creation of the braking command for the Normal Brake system for the BSCU 1 with a failure of the monitor system or the corresponding switch gate, causing the Control system sending erroneous braking command for this wheel. In comparison with Arch2, there are 7 less MCS due to the correction of the position of the accumulator.

At cardinality 3, we observe more than 2569 MCS. There are mainly combinations of one component of each BSCU failed causing the WBS to be in the Alternate Brake system, in addition with the failure of the meter valve or the hydraulic piston of the Alternate Brake system attached to the specific wheel. There are also some combinations about failures of Control system components like one of the components of BSCU 1 failed, leading to the use of BSCU 2, plus the failure of one of the components in BSCU 2 responsible for the creation of the brake command for the specific wheel and the monitor system of BSCU 2 failing to detect the error. There is one MCS less than in Arch2, due to the correction of the accumulator position.

For cardinality 4 and above, there is no MCS. The computation of the fault tree finished without applying restriction.

The probability is about 1.20e-04 which is more than allowed by the safety requirement. The failure conditions should be extremely improbable, which means with a probability of 1.0e-9 or less. But the safety requirement specified an “undetected” inadvertent braking. This aspect is not taken into account in our modeling (no detection of the braking force) which means that it would need another component to be in fault to cause the violation of the safety requirement, like explained previously. In this case, the probability should be lower than the one obtained.

For this TLE, the results for the 8 wheels are the same.

**Braking implies cmd w1** For this TLE, there are 10 MCS of cardinality 1: 3 about the meter valve of the Normal Brake system (failed open, failed last position or failed random position), 2 about the brake actuator (failed open or failed at the last position), 2 about the normal hydraulic piston (failed open or failed at the last position), 1 about the pedal position sensor sending an erroneous command, 1 about the alternate hydraulic piston failed open and 1 about the sensor of the wheel sending erroneous data.

At cardinality 2, there are 24 MCS. They are mainly combinations of a failure leading to the Alternate mode (Loss of the green pump or shutoff valve failed closed) with a failure of a component having an impact on the braking in the Alternate Brake system (alternate meter valve, alternate antiskid shutoff valve, alternate hydraulic piston, sensor of the pair of the wheel,...). There are also combinations of failures of one of the BSCU 1 component responsible for the commands creation of the wheel plus the switch gate corresponding to the command failed at last position (BSCU 1) or the monitor system of the BSCU 1 failing to to detect the wrong command creation. There are 16 MCS less than in Arch2 due to the correction of the accumulator position.

At cardinality 3, we observe 2647 MCS. There are mainly combinations of one component of each BSCU failed causing the WBS to be in the Alternate Brake system and the failure of the meter valve or the hydraulic piston of the Alternate Brake system attached to the specific wheel. Here too, there are fewer MCS (4) than in Arch2 due to the correction of the accumulator position.

At cardinality 4 and 5, there are thousands of MCS but less than in Arch2.

The fault tree computation terminates without restriction and generates MCS up to cardinality 5.

Concerning the probability, we do not have probability requirement for this property but, as in Arch2, we observe that its value is of the same order as the probability of inadvertent braking of one wheel without skidding (S18-WBS-R-0325-wheelX).

**Cmd implies braking w1** There are 13 MCS of cardinality 1: 3 about the meter valve of the Normal Brake system (failed closed, failed last position or failed random position), 2 about the brake actuator (failed full off or failed at the last position), 2 about the Normal hydraulic piston (failed full off or failed at the last position), 2 about the pedal position sensor sending an erroneous command or no data, 2 about the wheel sensor sending erroneous data or no data, 1 about the normal hydraulic fuse failed closed and 1 about the switch gate responsible for the brake command in the Normal mode failing at an intermediate position (No command sent).

At cardinality 2, the 30 MCS are mainly combinations of a failure leading to the Alternate mode (Loss of the green pump or shutoff valve failed closed) with a failure of a component having an impact on the Alternate Brake system and the braking of the wheel (alternate meter valve, alternate antiskid shutoff valve, alternate hydraulic piston, sensor of the pair of the wheel, ...). There are also combinations of the failure of one of the BSCU component responsible for the commands creation of the pair of the wheel with the switch gate corresponding to the command failed at last position (BSCU 1) or the monitor system of the BSCU 1 failing to detect the wrong command creation.

For cardinality 3, there are thousands of MCS. They are mainly combinations that can lead the WBS to be stuck in the Normal Brake system without commands or without pressure supply (one component of each BSCU failed with the shutoff valve failed closed or the selector valve failed last position), or failures leading to the Alternate Brake system (one component of each BSCU failed) with failure of one component of the Alternate Brake system causing the loss of wheel braking for the specific wheel (valve failed closed, piston or brake actuator failed full off, fuse failed closed, ...). In comparison with Arch2, the MCS including the shutoff valve failed open are not present here, due to the additional input of the selector valve.

For cardinality 4 to 5, there are thousands of MCS which are mainly combinations com-

| Arch/Prop | | Prob. | $\|mcs\| = 1$ | $\|mcs\| = 2$ | $\|mcs\| = 3$ | $\|mcs\| = 4$ | $\|mcs\| = 5$ | Full |
|---|---|---|---|---|---|---|---|---|
| arch3 | S18-WBS-R-0321 | 4.51e-10 | 0 | 6 | 1252 | 629 | - | N |
| | S18-WBS-R-0322-left | 1.00e-05 | 2 | 2 | 732 | 47583 | - | N |
| | S18-WBS-R-0322-right | 1.00e-05 | 2 | 2 | 732 | 47583 | - | N |
| | S18-WBS-R-0323 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | S18-WBS-R-0324 | 2.50e-11 | 0 | 1 | 0 | 38 | 10859 | N |
| | S18-WBS-R-0325-wheel1 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel2 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel3 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel4 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel5 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel6 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel7 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel8 | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | braking_implies_cmd_w1 | 1.25e-04 | 10 | 40 | 2651 | 7395 | 9636 | Y |
| | cmd_implies_braking_w1 | 1.13e-04 | 13 | 30 | 8053 | 3815 | 2873 | Y |

Table 7: Fault trees results for arch3 for the full set of faults (- represents a timed out computation)

posed of failure of Control system component with some of them including a component of the Alternate Brake system.

The fault tree computation terminates without restriction and generates MCS up to cardinality 6.

Concerning the probability, it is about 1.13e-04 but there is no probability requirement for this property.

**Summary and CBSA comparison** The reviewed MCS are consistent with what is expected and the computed probabilities are approximately is required by the requirements, adjusting for any requirement abstraction that was done. The effect of the correction of the accumulator position and the addition input for the selector valve have a direct consequence on the number of minimal cut sets in comparison of Arch2.

As in Arch2, the hierarchical fault tree generated from CBSA for each of the TLE have been confirmed to be an over-approximation of the fault trees generated by the MBSA. But the particular case of the property S18-WBS-R-0323, where we do not have any MCS computed for the full set of faults, we cannot state anything about the result of this comparison for this property.

### 5.2.4 Arch3

A sample of the results corresponding to the minimal cut sets (MCS) for each property at different cardinalities for the full set of faults for the MBSA is given in Table 7. The full results are given in Appendix K.

The observations are the same as in Arch2 [7]: the leaf components are the same and the Physical system is the same. The modification of the architecture of the Control system does not seem to have an impact on the generated fault trees.

### 5.2.5 Arch4

A sample of the results corresponding to the minimal cut sets (MCS) for each property at different cardinalities for the full set of faults for the MBSA is given in Table 8. The full results

[7] Note that the only difference is that we are talking about component of a specific BSCU channel in Arch3 instead of the component of a specific BSCU in Arch2

| Arch/Prop | | Prob. | $\|mcs\| = 1$ | $\|mcs\| = 2$ | $\|mcs\| = 3$ | $\|mcs\| = 4$ | $\|mcs\| = 5$ | Full |
|---|---|---|---|---|---|---|---|---|
| arch4 | S18-WBS-R-0321 | 4.51e-10 | 0 | 6 | 627 | 629 | - | N |
| | S18-WBS-R-0322-left | 1.00e-05 | 2 | 2 | 203 | 46287 | - | N |
| | S18-WBS-R-0322-right | 1.00e-05 | 2 | 2 | 203 | 46287 | - | N |
| | S18-WBS-R-0323 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | S18-WBS-R-0324 | 2.50e-11 | 0 | 1 | 0 | 2 | 8729 | N |
| | S18-WBS-R-0325-wheel1 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel2 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel3 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel4 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel5 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel6 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel7 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel8 | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | braking_implies_cmd_w1 | 1.25e-04 | 10 | 24 | 2647 | 4530 | 59 | Y |
| | cmd_implies_braking_w1 | 1.13e-04 | 13 | 30 | 7428 | 3815 | 1768 | Y |

Table 8: Fault trees results for arch4 for the full set of faults (- represents a timed out computation)

are given in Appendix L.

The observations are the same as in ARCH2BIS [8]: the leaf components are the same and the Physical system is the same. The difference of architecture of the Control system does not seem to have an impact on the generated fault trees.

## 5.3 Architecture comparison

### 5.3.1 Arch1 with the rest of the architectures

Basically, the findings confirmed the weaknesses of ARCH1: its number of "single points of failure", i.e. minimal cut sets of cardinality 1, is always greater, or equal what is computed for the other architectures. For the TLEs concerning the loss of wheel braking (S18-WBS-R-0321, S18-WBS-R-0322-left, S18-WBS-R-0322-right), the single points of failure due to the issue of the Control system in ARCH1 are the main difference at low cardinality. Another difference concerned the mechanical and the electrical command of the pedal linked to the same meter valve in ARCH1: in comparison with the other architectures, it seems that the redundancy of the commands sent to the meter valve prevent the failure of the pedal position sensor from appearing in the MCS, for the TLE about the loss of wheel braking. This is not the case for the TLE about inadvertent braking (S18-WBS-R-0324, S18-WBS-R-0325-wheelX).

For the TLE concerning the inadvertent braking with all wheels locked(S18-WBS-R-0323), there is no difference up to cardinality 5. After this point, the computation times out for all the architectures.

For the TLE concerning the inadvertent braking of all wheels (S18-WBS-R-0324), there is no difference up to cardinality 4 and the probability remains the same.

For the TLE concerning the inadvertent braking of one wheel without locking (S18-WBS-R-0325-wheelX), The MCS of ARCH1 are only composed of single points of failure. There is the same number as in the other architectures but they differ on one point: the failure of the brake command facility is not part of the MCS of the other architectures, due to the redundancy of the Control system. It is replaced by a MCS concerning the alternate hydraulic piston which can fail full-open and is not present in ARCH1 (only one piston in ARCH1).

Concerning the TLE about "braking implies cmd w1" and "cmd implies braking w1", we

[8] Note that the only difference is that we are talking about component of a specific BSCU channel in ARCH4 instead of the component of a specific BSCU in ARCH2BIS

also observe more single points of failure in Arch1 than in the other architectures. These are mainly due to the issue of the Control system and the lack of redundancy.

The probabilities associated with the TLEs about the loss of wheel braking (S18-WBS-R-0321, S18-WBS-R-0322-left, S18-WBS-R-0322-right) are also greater than in the other architectures. But the probability associated with the inadvertent braking of one wheel without locking (S18-WBS-R-0325-wheelX) is better in Arch1 than in the other architectures (9.63e-5 in Arch1, 1.20e-4 in the other architectures). This is due to the fact that even if there is the same number of minimal cut sets of cardinality 1, neither the components at fault nor the reliabilities are the same: In Arch1, at cardinality 1, we have 9 MCS, including one about the failure of the brake command facility sending erroneous commands. In the other architectures, there are 9 MCS too, but the failure of the brake command facility is not part of them, due to the redundancy of the Control system. There is an additional MCS about the Alternate hydraulic piston which can fail full-open. Since the probability of the hydraulic piston to fail open (3.3e-5) is greater that the brake command facility to fail (9.0e-6), the probability for this TLE is greater in the other architectures than in Arch1 (9.63e-5 - 9.0e-6 + 3.3e-5 = 1.20e-4). The influence of the probability of the failure of the alternate hydraulic piston also has the same kind of effect on the probability for the TLE “braking implies cmd w1” for the other architectures.

### 5.3.2 Arch2 to Arch3 (Similarly Arch2bis to Arch4)

The fault trees for the pair Arch2 and Arch3 are the same, which suggests that the modification of the Control system (i.e. the difference between these two architectures) has no impact on the safety requirements. Similar observations hold for the pair Arch2bis and Arch4.

This is to be expected, since the change in the Control system between Arch2 and Arch3 (similarly between Arch2bis and Arch4) is triggered by a trade study aiming at reducing the cost and easing the installation and the maintenance, but the two control systems are designed according to the same redundancy principles, i.e. double control unit. The difference is that in one case the two control units can be physically positioned in different places, i.e. two BSCUs, while in the other they are part of a unique sub-system, i.e. one BSCU, (which can, in very rare situations, break the assumption of independence of the two control units). Common Cause Analysis (CCA), in particular Zonal Safety Analysis (ZSA), could confirm this point, and will be part of future work.

### 5.3.3 Arch2 to Arch2bis (Similarly Arch3 to Arch4)

The superiority of Arch2bis on Arch2 (and similarly of Arch4 on Arch3) is demonstrated by a lower number of minimal cut sets with cardinality greater than 1.

For the TLEs about the loss of wheel braking (S18-WBS-R-0321, S18-WBS-R-0322-left, S18-WBS-R-0322-right), the lower number of minimal cut sets appears at cardinality 3. There are hundreds fewer MCS due to the additional input from the Control system validity for the selector valve in Arch2bis (similarly Arch4). This additional input prevents the consequences of a failure of the shutoff valve failing open.

For the TLE about the inadvertent braking of all wheels with locking (S18-WBS-0323), there is no difference up to cardinality 5 and the computation times out above 5. One observation is that, for the set of faults set1 where the faults of the components of Physical system are implied (in particular the shutoff valve, the selector valve and the accumulator) we are able to finish the computation of the fault tree for Arch2bis without restriction, but not for Arch2.

Concerning the inadvertent braking of all wheels (S18-WBS-R-0324), a lower number of MCS starts appearing at cardinality 4 and 5. In these cases, the correction of the position of the accumulator is responsible for the decrease of MCS for Arch2bis (similarly Arch4).

For the TLEs concerning the inadvertent braking of one wheel without locking (S18-WBS-R-0325-wheelX) the lower number of MCS appears at cardinality 2. There is one MCS less in Arch2bis, due to the correction of the position of the accumulator.

For the TLE “Braking implies cmd w1”, there are fewer MCS starting from cardinality 2 in Arch2bis, due to the correction of the accumulator position.

For the TLE “Cmd implies braking w1”, there are fewer MCS startingfrom cardinality 3 in Arch2bis due to the additional input of the selector valve from the Control system validity.

In conclusion, we can observe that the two modifications applied to Arch2bis (similarly Arch4) result in a reduction in the number of MCS for the different TLEs: the additional input of the selector valve in Arch2bis (similarly Arch4) has a beneficial impact on the number of MCS for the TLEs concerning the loss of wheel braking (S18-WBS-R-0321, S18-WBS-R-0322-left, S18-WBS-R-0322-right, Cmd implies braking w1 ) whereas the correction of the accumulator position in Arch2bis (similarly Arch4) has a beneficial impact on the number of MCS for the TLEs concerning inadvertent wheel braking (S18-WBS-0324, S18-WBS-R-0325-wheelX, Braking implies cmd w1).

# 6 Conclusion

We presented a complete formal analysis of the AIR6110 [25], a document describing the informal design of a Wheel Brake System based on Aerospace Recommendation Practices ARP4754A and ARP4761. We covered all the main phases of the described process, and modeled the case study by means of a combination of formal methods including contract-based design, model checking and safety analysis. We were able to produce modular descriptions of the four architecture variants described in the AIR6110 plus an additional one, and to analyze their characteristics in terms of a set of five chosen safety requirements, automatically producing over 3000 fault trees, as well as quantitative reliability measures. We demonstrated that the formal approach is effective in identifying issues in an architecture or implementation, and can provide information through counter examples, traces or other means that can assist the designer in correcting those issues. We also demonstrated that a formal approach can in some instances help detect issues earlier in the design cycle, and provide effective means for regression testing. For instance, we remark that one of the analyzed architectures (Arch2bis) was the result of detecting an unexpected dependency in the phases of the AIR6110. Specifically, the trade study on the control system (leading from Arch2 to Arch3) was carried out on an architecture suffering from a misplaced position of the accumulator (fixed in Arch4). This flaw was detected both by formal verification and safety analysis means on Arch2. The results of the analyses also show that the modification of the Control system applied in Arch3 triggered by trade study has no impact on the safety objectives of the WBS. Specifically, the five chosen safety requirements are still met, as expected in the AIR6110. In the following, we discuss some lessons learned, related work in the literature, and outline directions for future activities.

**Lessons learned** The value in going from an informal description to a formal model was clearly recognized: the AIR6110 omits important information that is assumed to be background knowledge. The ability to produce the artifacts of the traditional design flow (e.g., architectural diagrams for visual inspection, fault trees) supported the interaction with subject matter experts, who were able to provide fundamental information to increase the accuracy of the models. As modelers, we also observed that the act of writing formal behavioral contracts in the model helps in reasoning about the architecture specification and informally detecting possible errors.

Model-based safety analysis is a fundamental factor for this kind of application. First, it provides for automated construction of models encompassing faults from models containing only nominal behaviours. Second, traditional verification techniques, which allow to prove or disprove properties, are not sufficient: the automated synthesis of the set of minimal cut sets (i.e. the configurations causing property violations) is required to support the informal process and to provide a suitable granularity for the comparison of various architectural solutions. This approach also provides strong support for trade studies.

There is also a particular aspect to take into account in further version of our modeling concerning how to validate the recovery modes designed in the architectures at early stages. In the nominal mode, if the components are not in failure, we should not be able to observe the functioning of the recovery modes of the system. Currently, we modeled some components, like the BSCU components or the hydraulic pump, to react to the input of the environment in order to be able to observe this functioning. For instance, if the pump is not supplied with hydraulic or power by the environment, it cannot supply pressure to the hydraulic circuit. If the pump does not supply the hydraulic circuit, it can be considered as a loss of pressure in the circuit, and the selector valve can make the system evolve through the different recovery modes (Normal mode, Alternate mode, Emergency mode). As it is really convenient to observe the functioning of the different recovery modes earlier in the nominal model, it can be problematic for the next phases. Indeed, to obtain consistent MCS for the MBSA, we must apply an assumption on the properties saying that the environment always supplies power or hydraulic. Otherwise, the failures of the components due to the inputs from the environment are not taken into account by the tool as a failure, and the MCS are not consistent. One way of addressing this problem is to define the environment as a component with its own failure modes. This results in a more precise MCS that takes into account failures modes of the environment, but implies that validation of the recovery modes will be made in the safety assessment phase. Further investigation is needed on this point.

A key factor of this case study is the availability of automated and efficient analysis engines. The availability of IC3 and its extensions to the formal verification and to the computation of minimal cut sets allows for the analysis of architectures that are completely out of reach for BDD-based algorithms. In particular, for the formal verification, the models must be simplified to obtain a result with BDD-based algorithms. Moreover, the IC3 engine remains faster than BDD-based over a simplified model.

The use of an architectural modeling language, as proposed in the Contract Based approach supported by OCRA (and its integration with nuXmv), allows reusing both models and contracts. For example, the similar architectures (e.g., Arch3 and Arch4) share a very large part of their models. This also makes it possible to analyze architectural variants with moderate effort. Concerning the specification of the contracts in the architectures, we observed that the verification of the refinement is significantly more performant when the contracts are split. For example, as a first try, we specified the contracts for the eight wheels as one huge contract in the Physical system. The verification of the refinement for Arch2 was longer than the split version of the contract. The split of the contracts for each wheel simplifies the verification and eases the review of traces (counter-example generated in case of invalid contract) for the user.

There is a fundamental role for contract-based design. Its key advantages are the ability to mimic the informal process, thus ensuring traceability, and to support proof reuse. Contract-based design also supports the construction of Hierarchical Fault Trees, which are a fundamental artifact compared to the flat presentation of the set of minimal cut sets. The CBSA approach outlined in [5] enables for hierarchical FT generation, which are much easier to compute, and exhibit more structure when compared to a flat presentation of minimal cut sets. The open problem is how to evaluate the amount of approximation associated with the method.

**Related work** The WBS described in ARP4761 has been used in the past as a case study for techniques on formal verification, contract-based design and/or safety analyses (see, e.g., [20, 21, 11, 9]). With respect to these works, this case study is much more comprehensive, and the only one to automatically produce fault trees. In [5], contract-based fault-tree generation is applied to the ARP4761 WBS, but on a much smaller architecture than those considered in this paper. The work presented in this report is unique in the literature, in that it takes into account the process described in AIR6110 and analyzes the differences between the various architectures.

There are many applications of formal methods in the industrial avionics process, e.g. ESACS [12], ISAAC [19], and MISSA [22] projects which pioneered the ideas of model extension and model-based safety assessment, and proposed automatic generation of Fault trees/MCSs. But we are not aware of works combining contract-based design, formal verification, and model-based safety analysis (with automated fault tree generation) as in the methodology described in this case study.

**Future work** We will continue this work along the following directions, also driven by the findings in the case study. We will explore the use of alternative and more expressive modeling formalisms that may be more adequate to describe systems at a higher level of detail. For example, we will consider the use of SMT and more expressive logics, both on discrete and hybrid traces [8]. We will also attempt to introduce delays in the behavior of the components, as currently they have all an instantaneous behavior.

We will try to refine the failure modes defined for the leaf components. We can extend them and include new ones based on expert clarifications. Concerning the probability, we can review their precision and try to make component bias explicit in their definition. For example, the bias of the meter valve component is to fail closed. This failure mode should be considered as the high level loss of the component, and the high level probability of failure. The nominal ratio of probabilities of loss to erroneous failure is approximately 10:1. Another lead will be to discuss how it will be possible to take into account the exposure time of the components. The definition of CCA for the WBS will also be an interesting lead. Finally, we can also think about extending xSAP fault library with new failure modes commonly encountered in the domain.

Contract-based design poses important challenges in terms of debugging. In particular, there is a need for suitable diagnostic information to support contract formulation (e.g., to understand why a certain contract refinement does not hold).

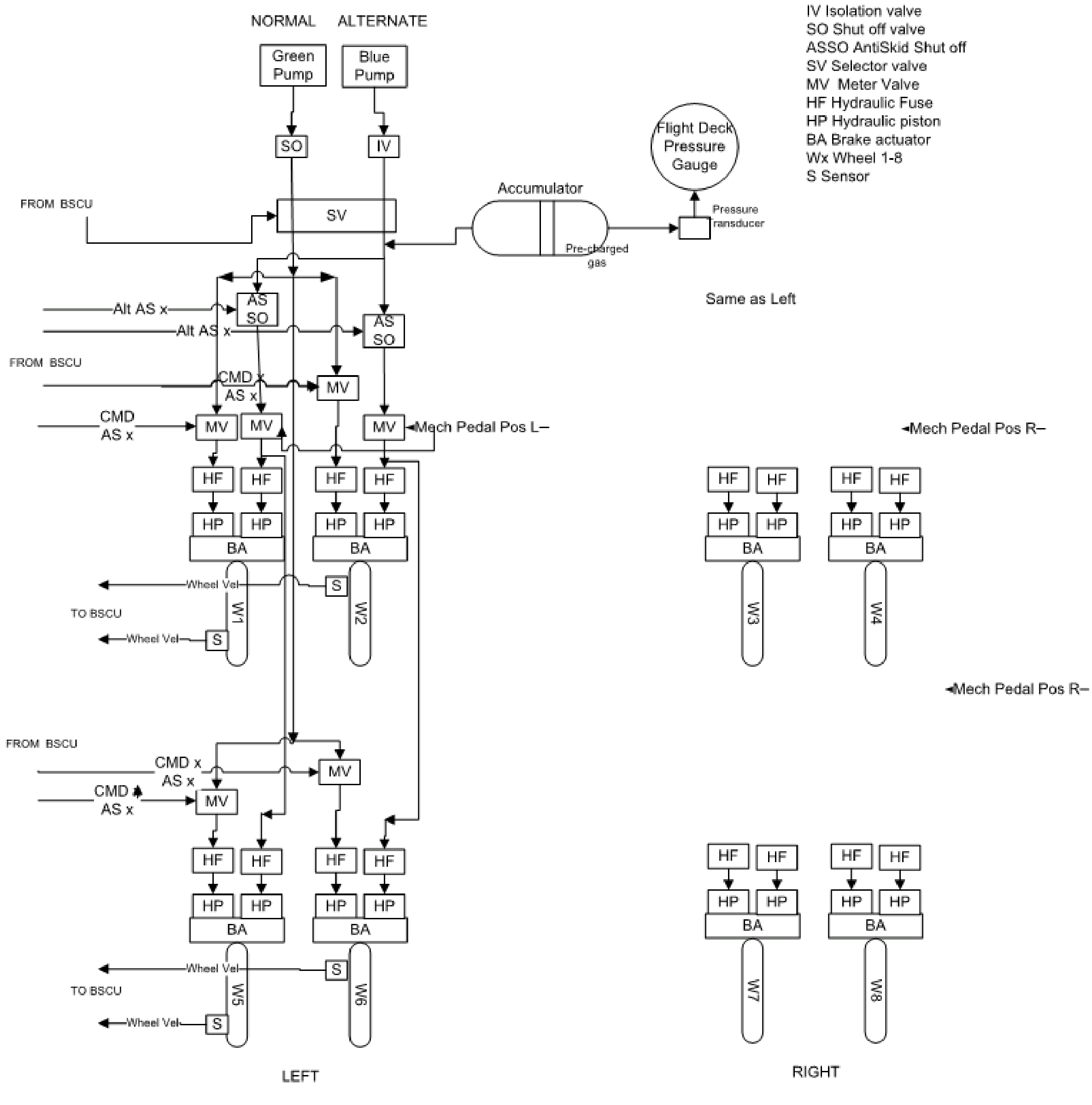
Another direction concerns increasing scalability for safety analysis. Realistic cases require the analysis of tens of thousands of minimal cut sets. We will investigate techniques to gain efficiency by introducing approximations (e.g., limiting cardinality and likelihood of cut sets); an important requirement will be the ability to calculate the degree of approximation of the result. We will also work on ways to reduce the efforts in comparing MCS and fault trees of different architectures possessing the same leaf components and failure modes.

# Appendix

# A Additional information about the WBS

Descriptions of the following elements are based on the understanding of descriptions from AIR6110 and clarifications provided.

## A.1 Clarifications about the hydraulic circuit



Notes:
- For Blue (Alt) Circuit, there is a single anti-skid shut off valve and single meter valve per wheel pair; pairs are W1-W5; W2-W6; W3-W7;W4-W8.

Figure 38: Detailed description of the architecture of the hydraulic circuit

## A.2 Description of the hydraulic supply

### A.2.1 Hydraulic pump

The hydraulic pump supplies hydraulic pressure to the hydraulic circuits of the Wheel Brake System. The pump is supplied with a power source and a hydraulic source.

### A.2.2 Accumulator

The accumulator is a reserve of pressured hydraulic fluid, with pressure provide by a pre-charged gas container. The reserve must be sufficient to provide enough pressure to apply braking force for the required number of presses of the braking pedal. In the WBS, the blue pump should charge the accumulator with hydraulic fluid. The accumulator supplies the Alternate Brake System in the Emergency mode when the blue pump is lost and the Normal mode is not available. In this case, the loss of the blue pump in Alternate mode will imply the use of the hydraulic fluid from the accumulator with the isolation valve preventing the accumulator hydraulic fluid from traveling back to the blue pump.

The accumulator must indicate pressure available to the flight deck. One mechanism might be to report pressure through the BSCU and an electronic signal.

## A.3 Description of the controls

### A.3.1 Brake pedals

There is one brake pedal for the brakes on the left landing gear and another for the brakes on the right landing gear. Each are connected electrically or mechanically to other parts of the WBS. Electrically, the pedals send a signal to the BSCU to activate braking. Mechanically, the pedals are linked directly to the meter valves of the Alternate Brake system.

### A.3.2 BSCU

The BSCU must provide commands (Brake and anti-skid commands) to control the hydraulic pressure supplies to the brake of each wheel. It must also provide brake system annunciation for display and provide health monitoring for the brakes to detect their fatigue prior to their failure. The BSCU is interfaced with other components of the WBS or aircraft system.

## A.4 Description of the valves

### A.4.1 Shutoff valve

The shutoff valve is used to close the circuit depending on an electrical command.

In the WBS, the shutoff valve is provided in the NORMAL path to help meet the “no single failure” requirement for unintended application of brakes. It is closed if the BSCU becomes invalid.

### A.4.2 Isolation valve

The isolation valve prevents fluid flow back to pump from the accumulator.

### A.4.3 Selector valve

The selector valve selects which hydraulic circuit (Normal, Alternate) will be connected to a hydraulic pressure source. It is a mechanical device[9] with no feedback[10] (i.e., no pump status sent to the BSCU).

In the WBS, the reduction of the hydraulic pressure coming from the green supply, due to the loss of the green pump or from the removal of the pressure by the BSCU due to the presence of faults, causes the valve to automatically connect the blue supply to the Alternate Brake System and to cut the supply to the Normal Brake System.

### A.4.4 Antiskid shutoff valve

The antiskid shutoff valve is controlled by an electrical command to control the hydraulic pressure. This valve is used to reduce hydraulic pressure to the brakes in order to prevent locking of the wheels.

### A.4.5 Meter valve

The meter valve must control pressure to the commanded level. In the WBS, the meter valve has two roles:

- In the Normal mode, each meter valve is commanded only by an electrical command to control pressure to the demanded level, taking into account the anti-skid function.
- In the Alternate mode, each meter valve is commanded only by the mechanical position of the pedals.

[9] `http://en.wikipedia.org/wiki/Shuttle_valve`

[10] An alternative design might incorporate "smart" selector valve with feedback from the pumps to the BSCU to electronically pick the pump to be used. A comparison would illuminate differences among the respective failure modes

# B WBS Arch1 architecture decomposition

## B.1 Environment

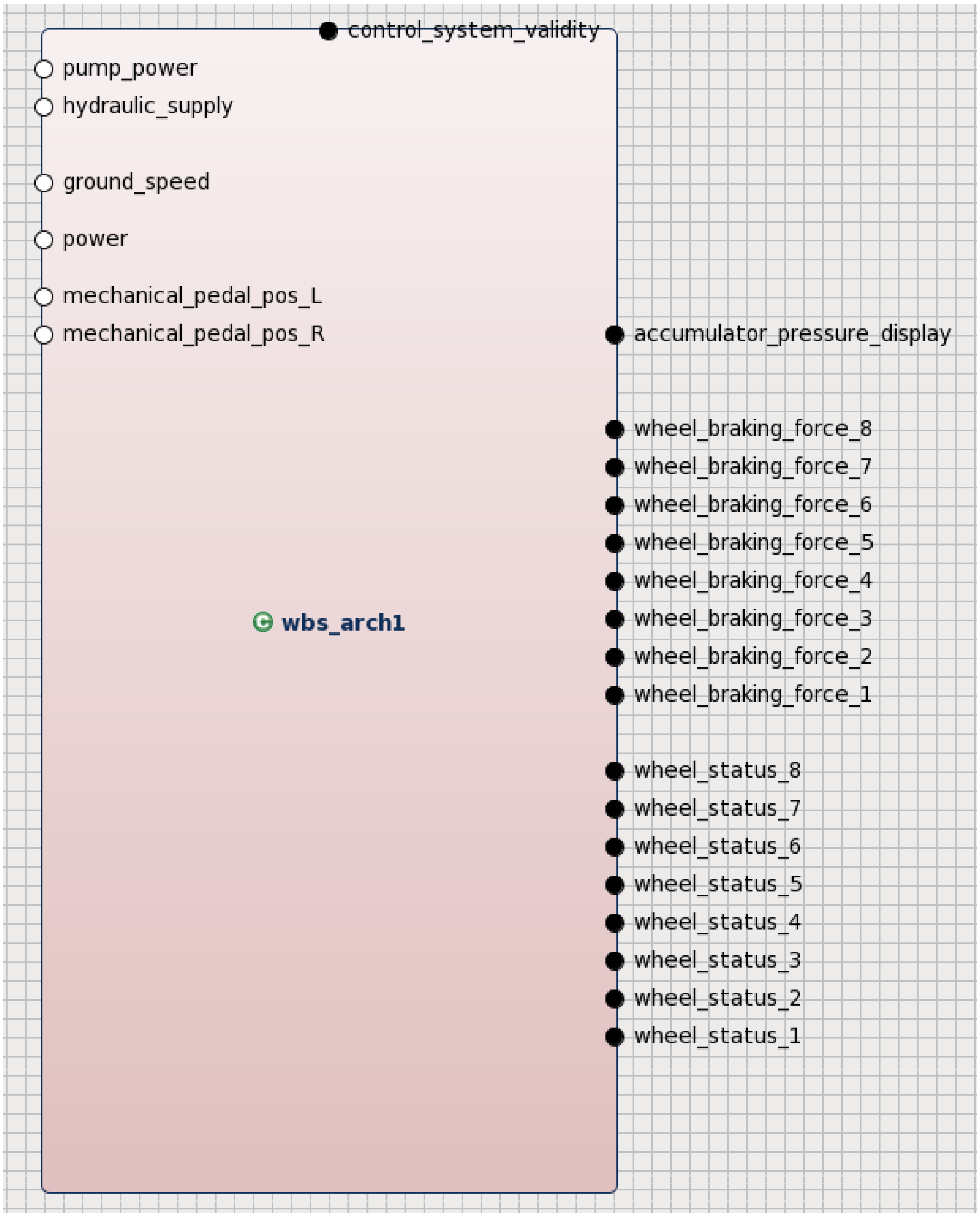


Figure 39: Environment of the Wheel Brake System

## B.2 Wheel Brake System

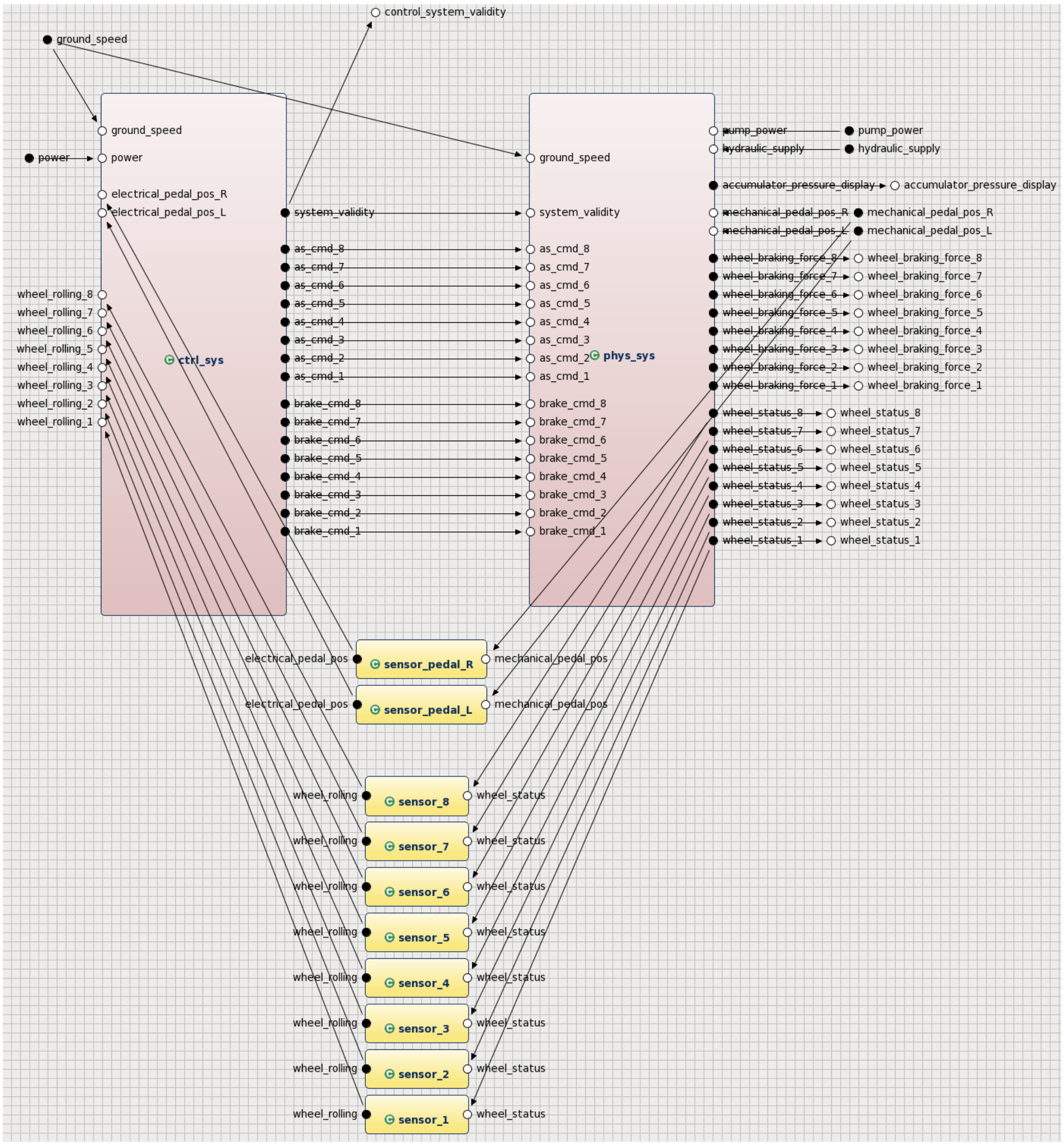


Figure 40: Wheel Brake System decomposition

## B.3 Control System

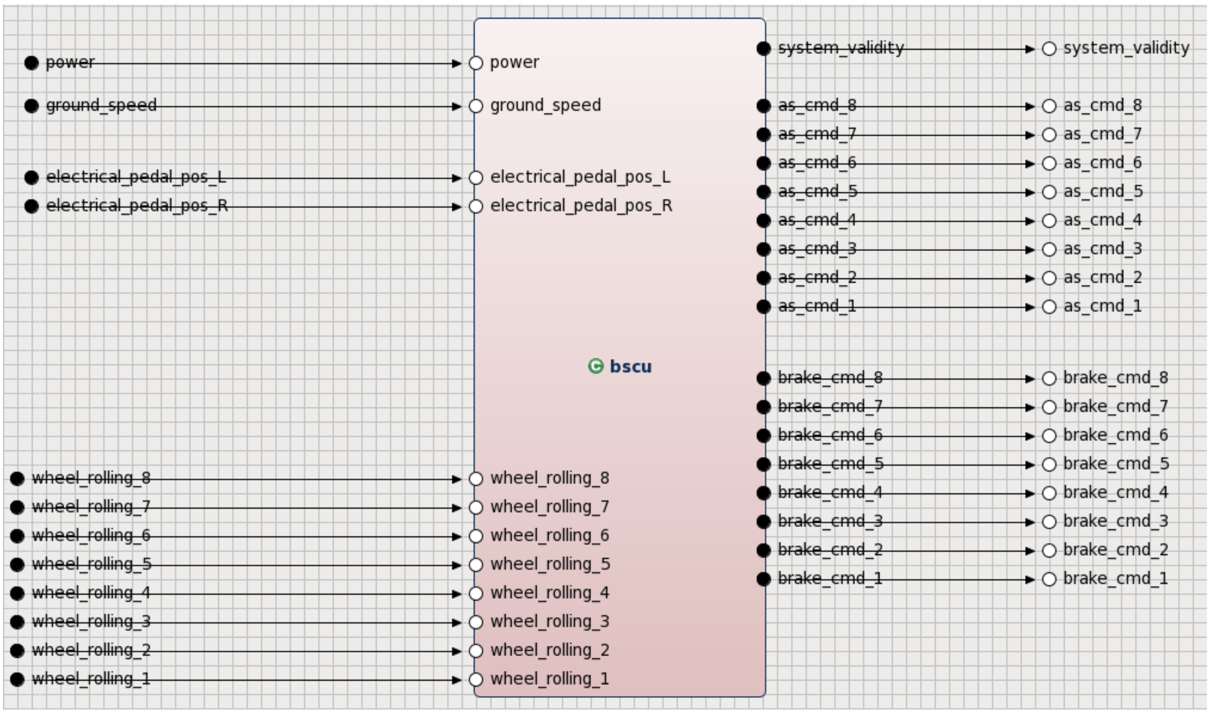


Figure 41: Control System decomposition

## B.4 BSCU

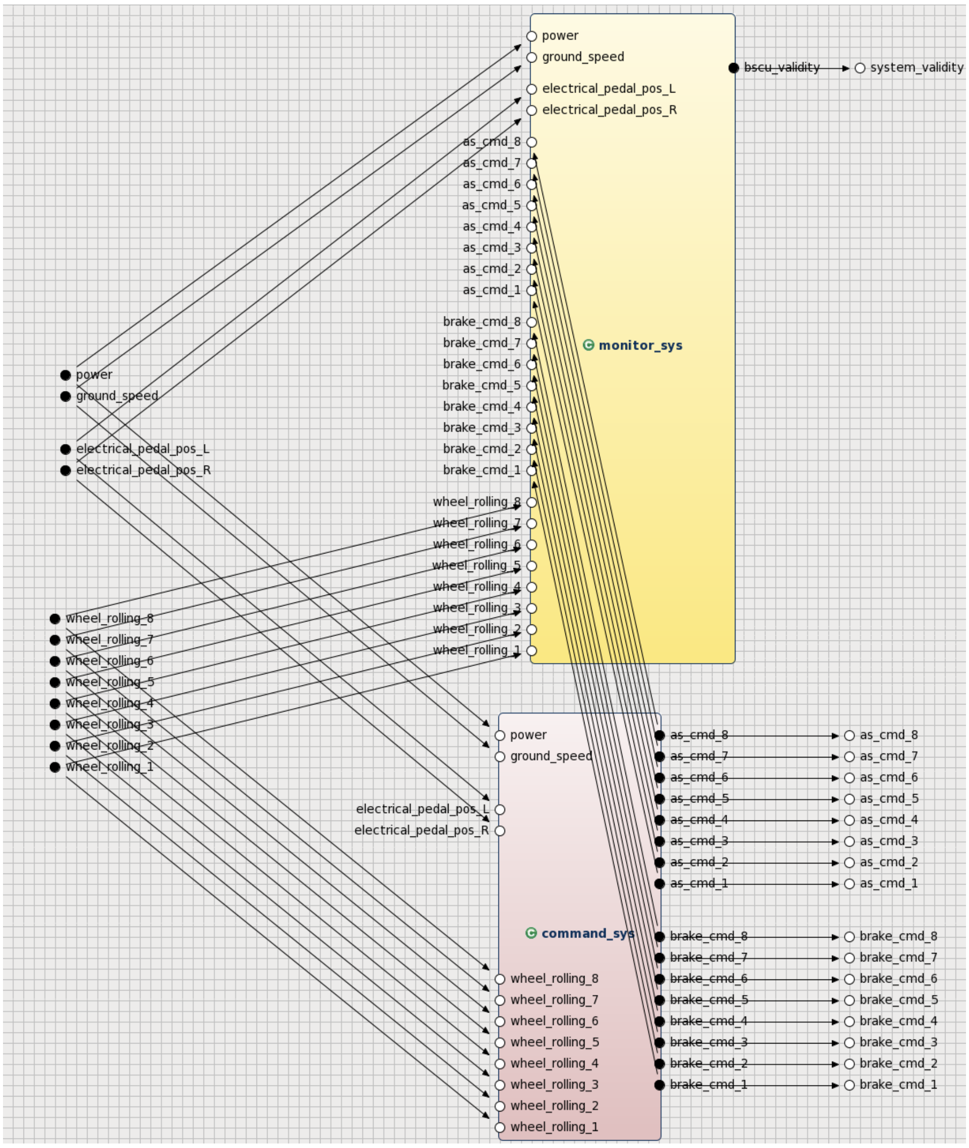


Figure 42: BSCU decomposition

## B.5 Command System

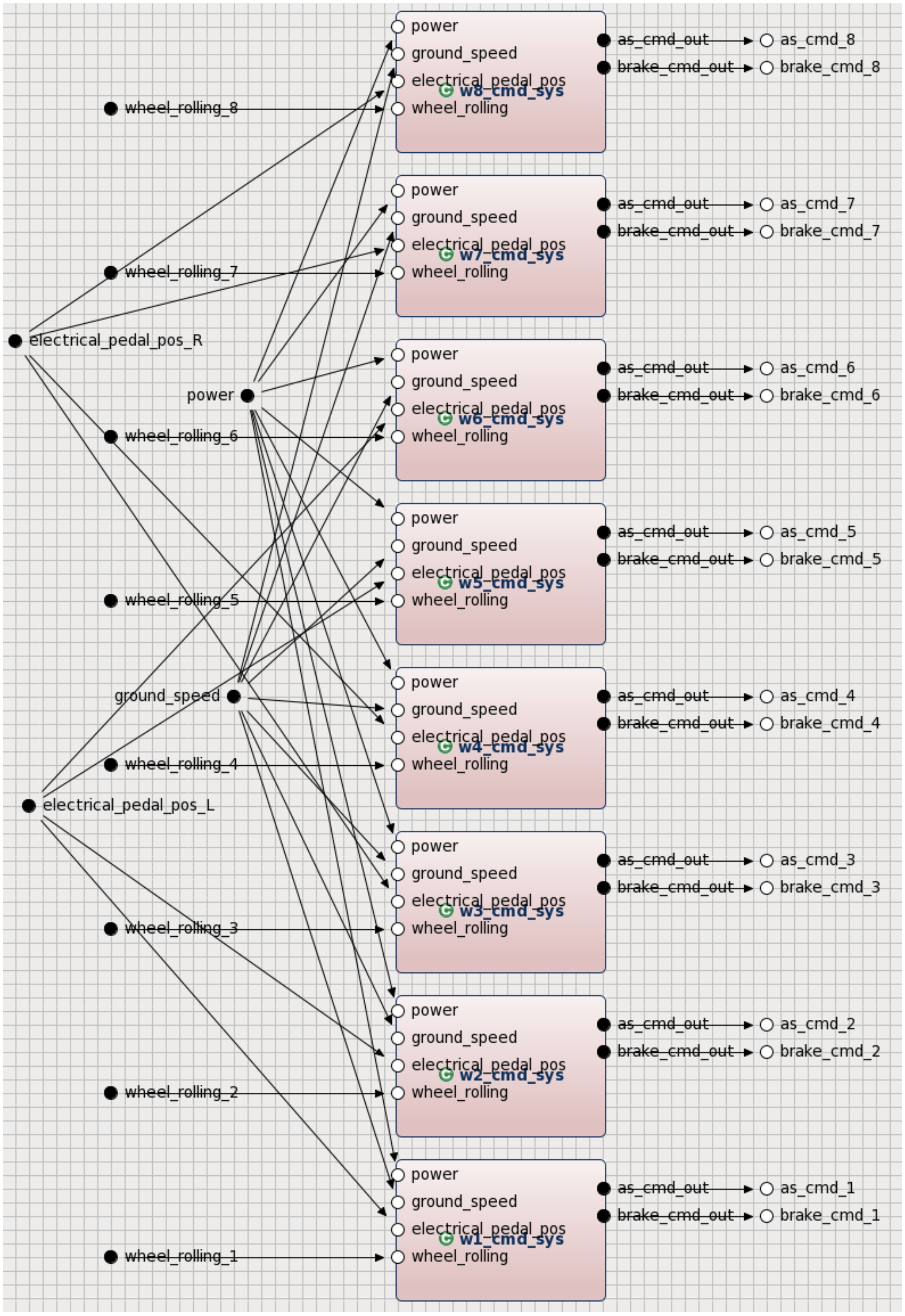


Figure 43: Command System decomposition

## B.6 Wheel Pair Command System

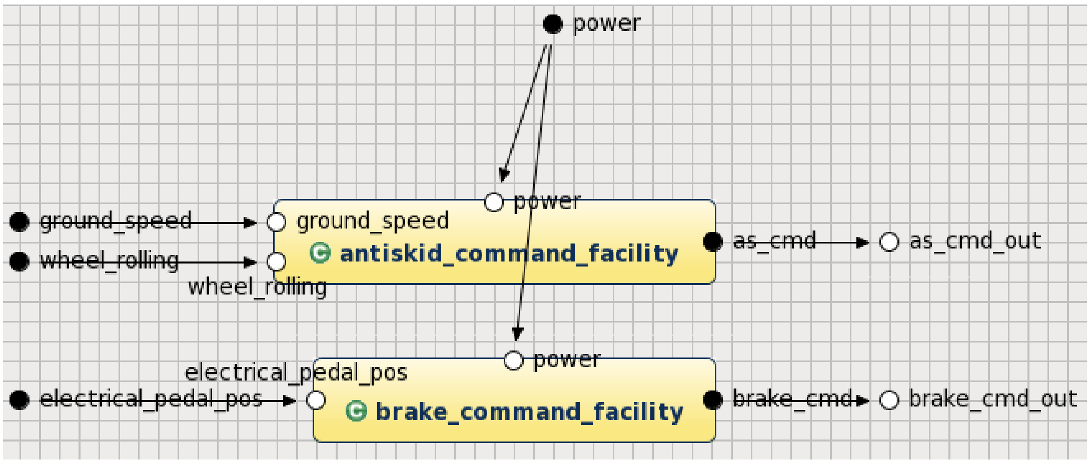


Figure 44: Wheel Command System decomposition

## B.7 Physical System

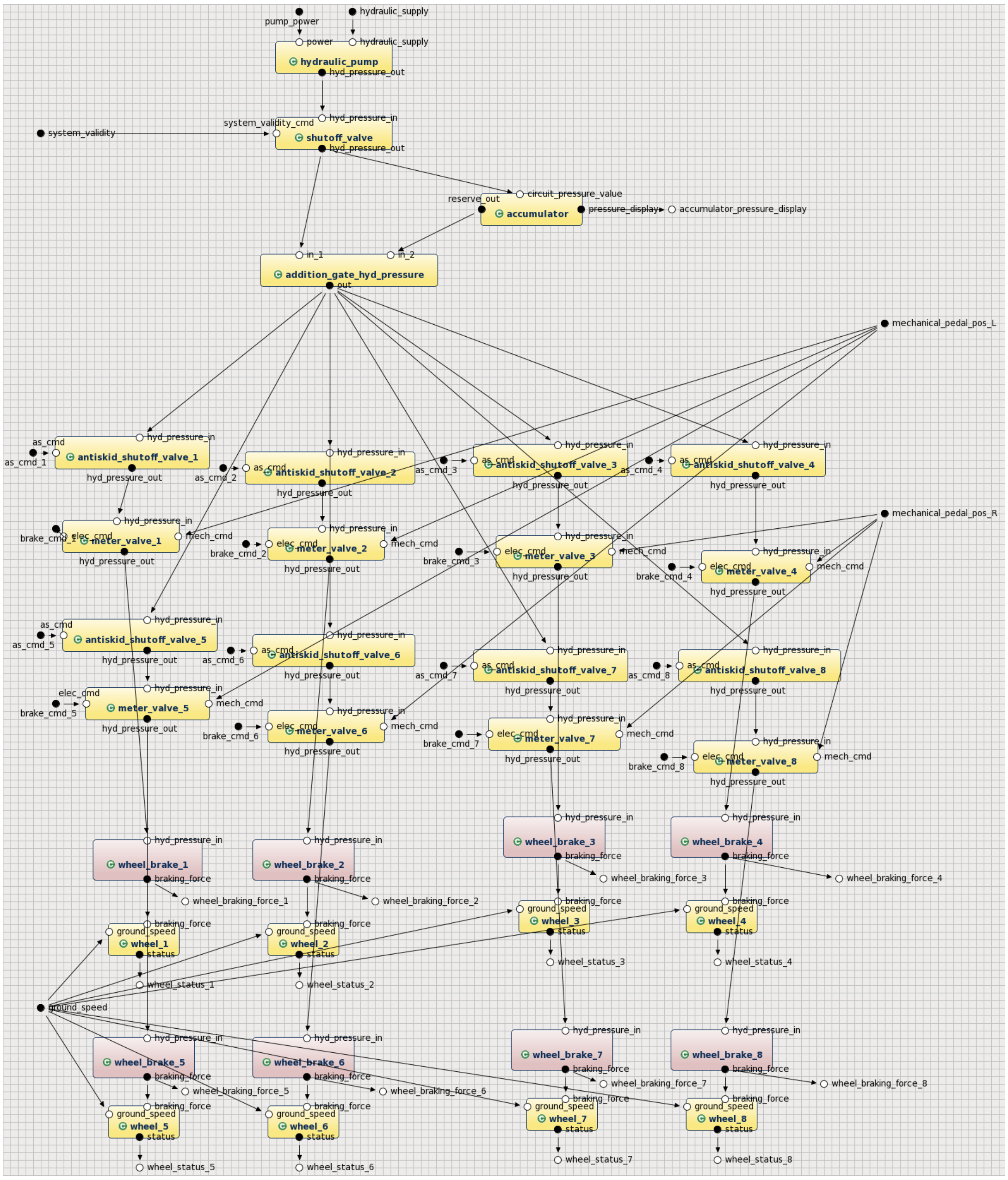


Figure 45: Physical System decomposition

### B.8 Wheel Brake

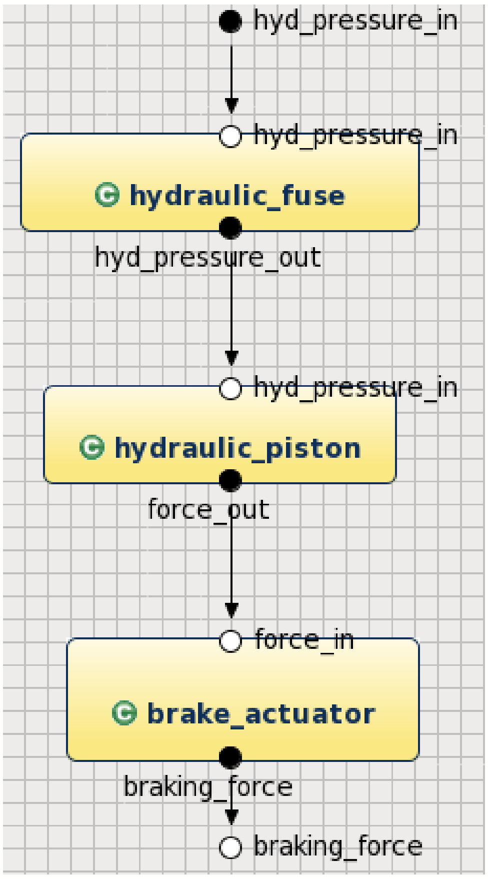


Figure 46: Wheel Brake decomposition

# C WBS Arch2 architecture decomposition

## C.1 Environment

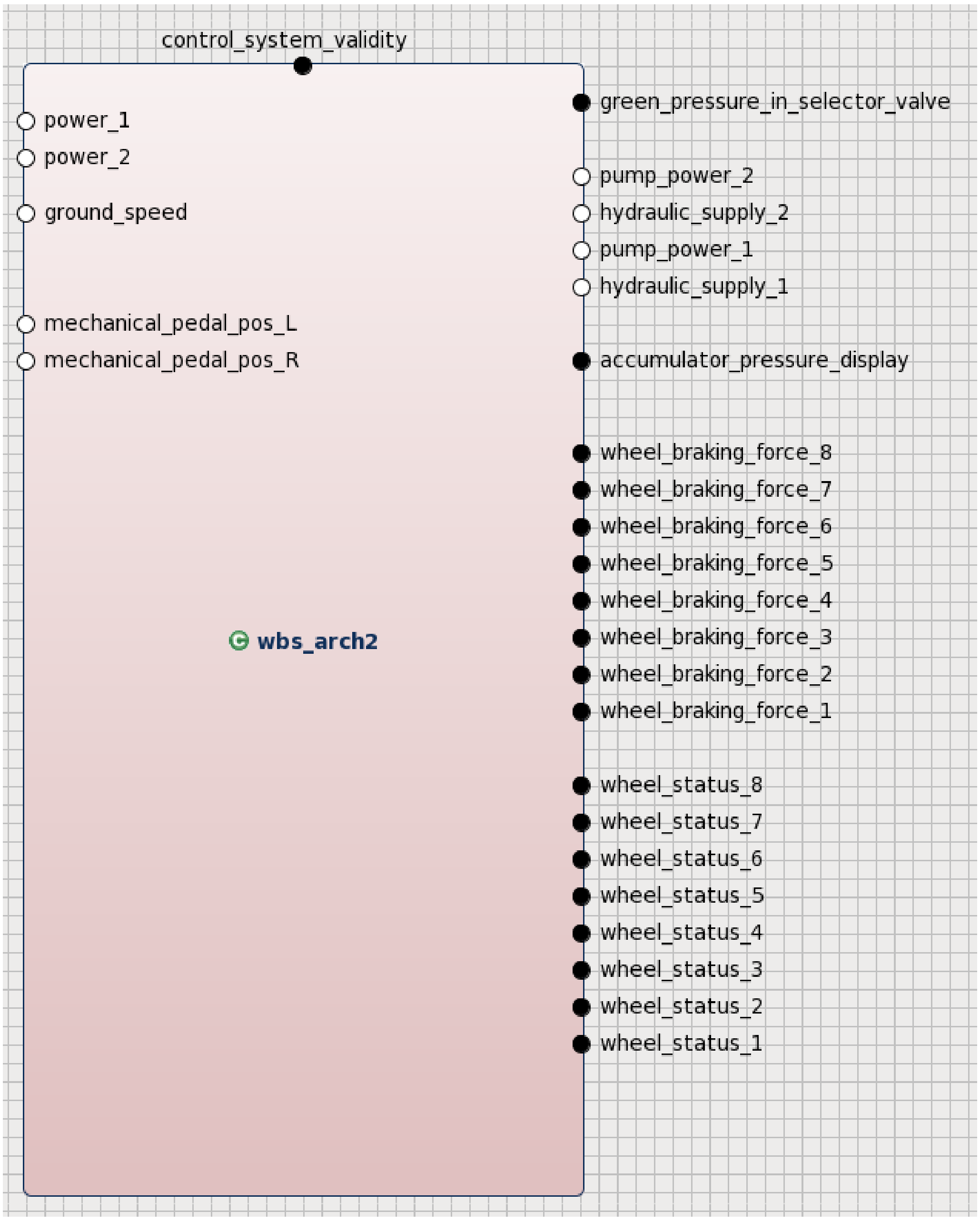


Figure 47: Environment of the Wheel Brake System

## C.2 Wheel Brake System

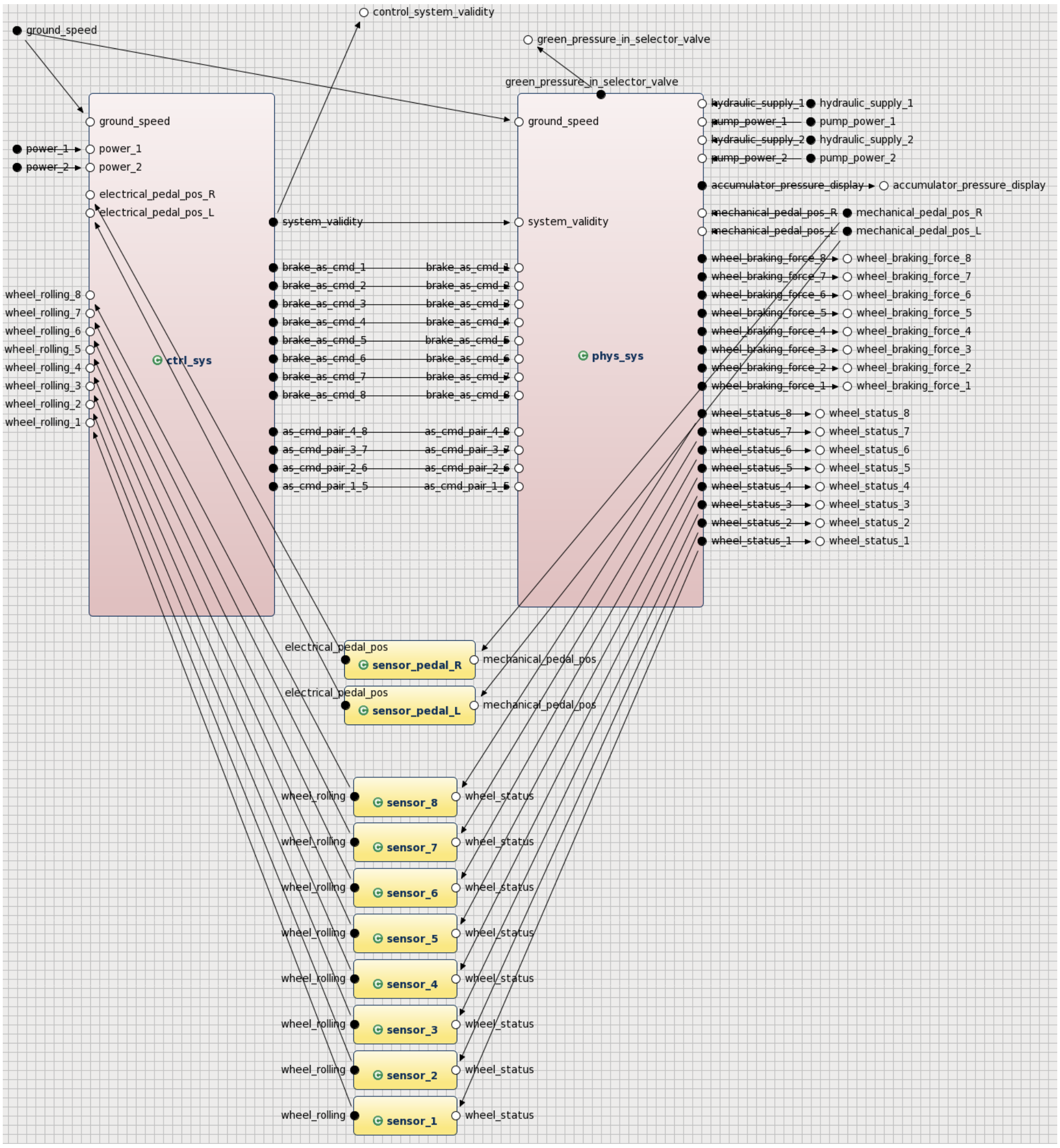


Figure 48: Wheel Brake System decomposition

## C.3 Control System

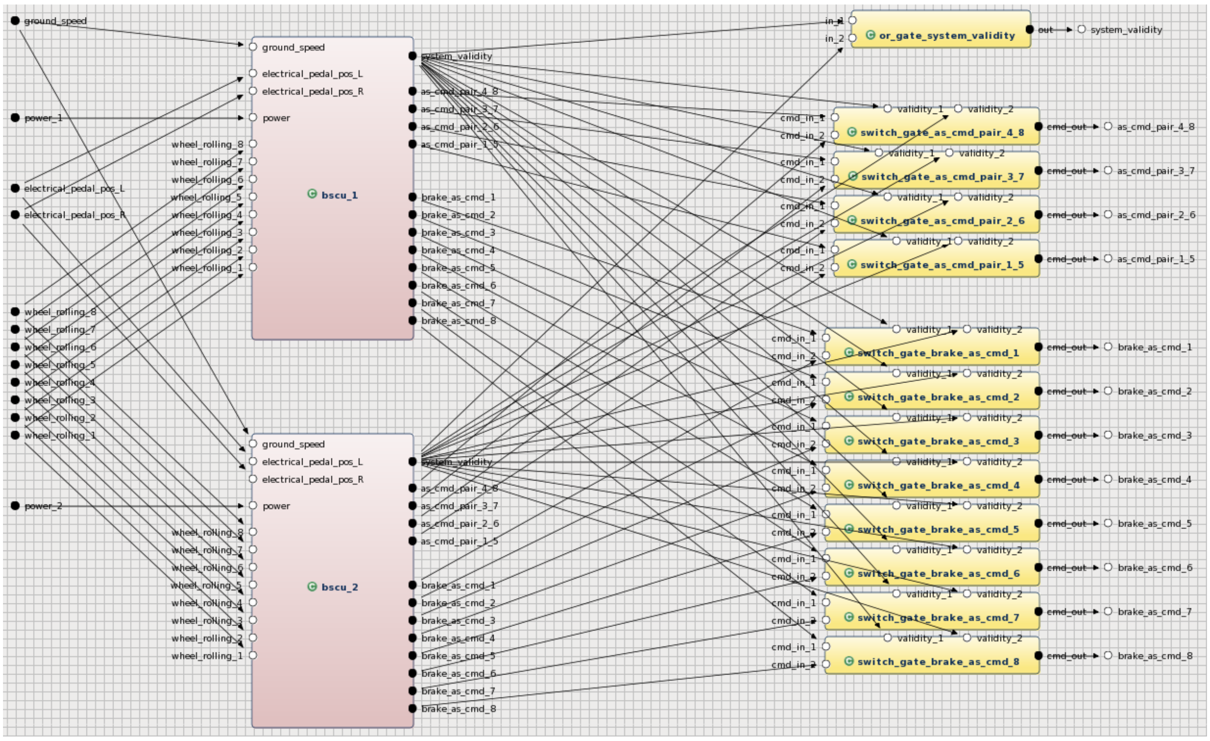


Figure 49: Control System decomposition

## C.4 BSCU

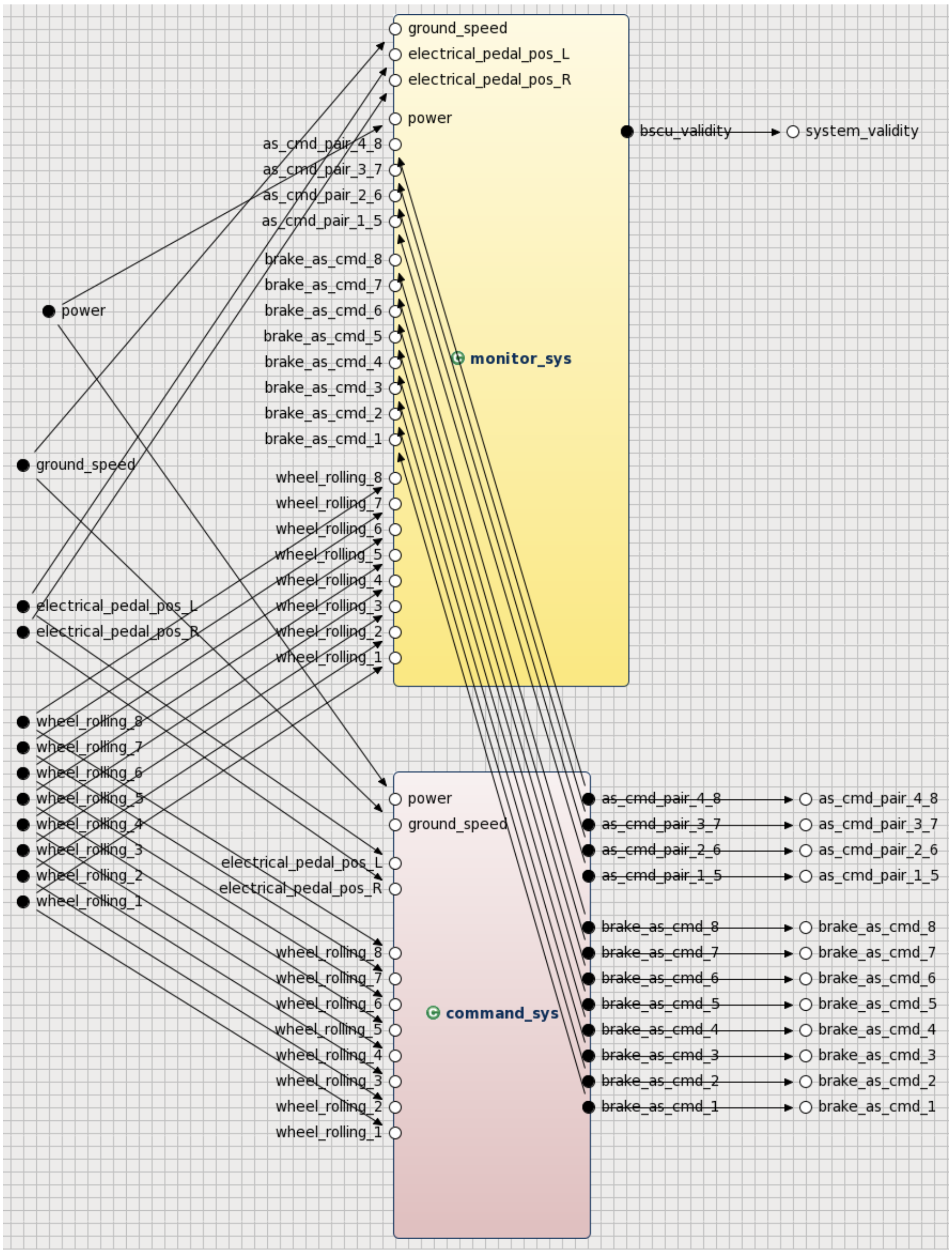


Figure 50: BSCU decomposition

## C.5 Command System

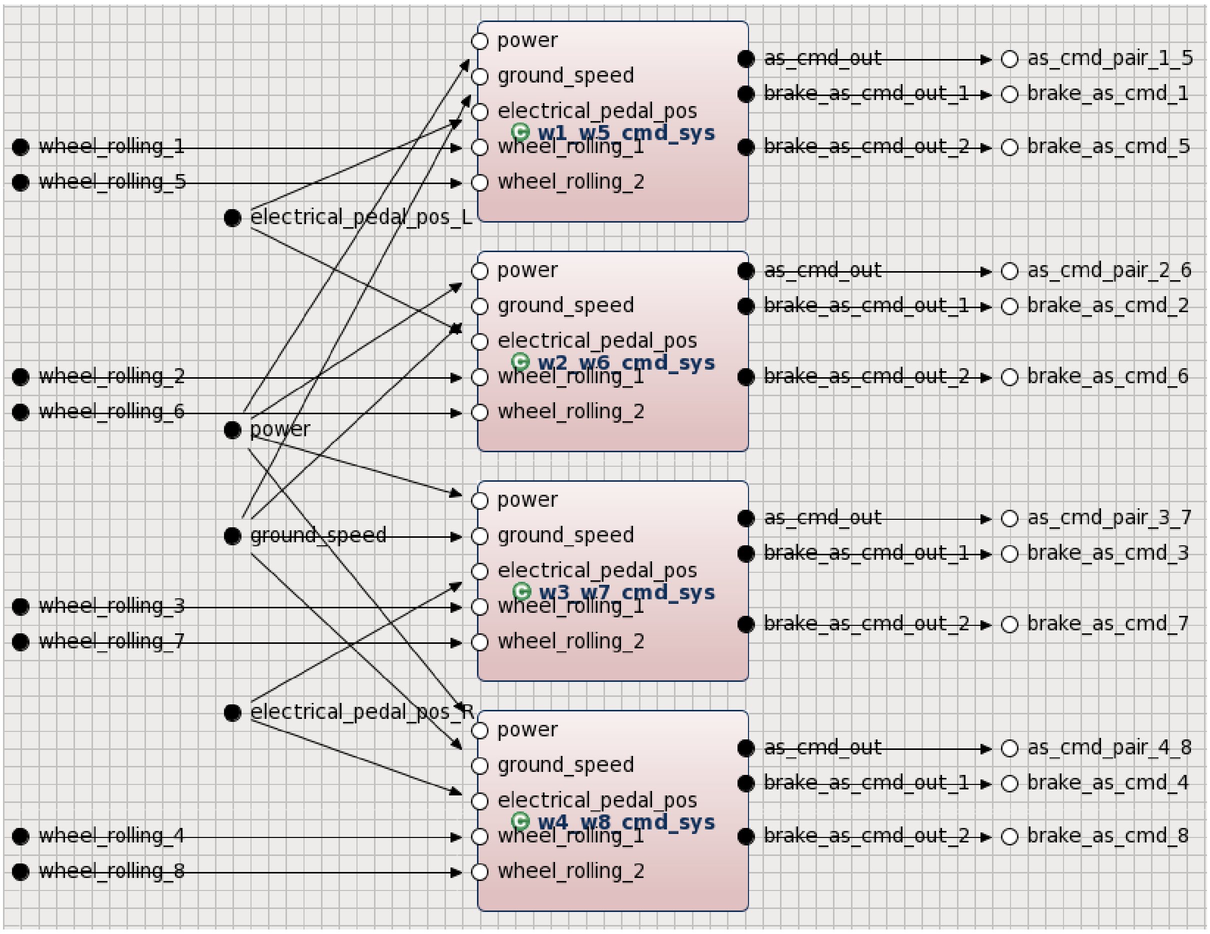


Figure 51: Command System decomposition

## C.6 Wheel Pair Command System

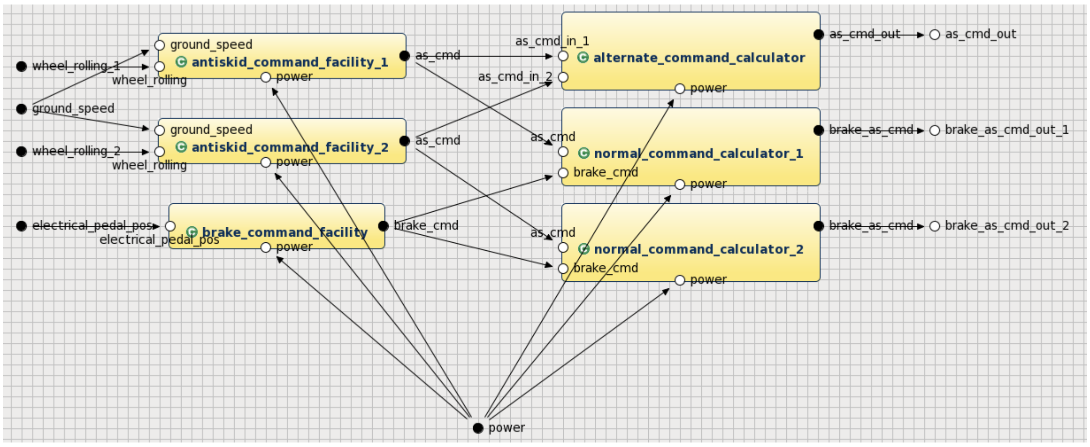


Figure 52: Wheel Pair Command System decomposition

## C.7 Physical System

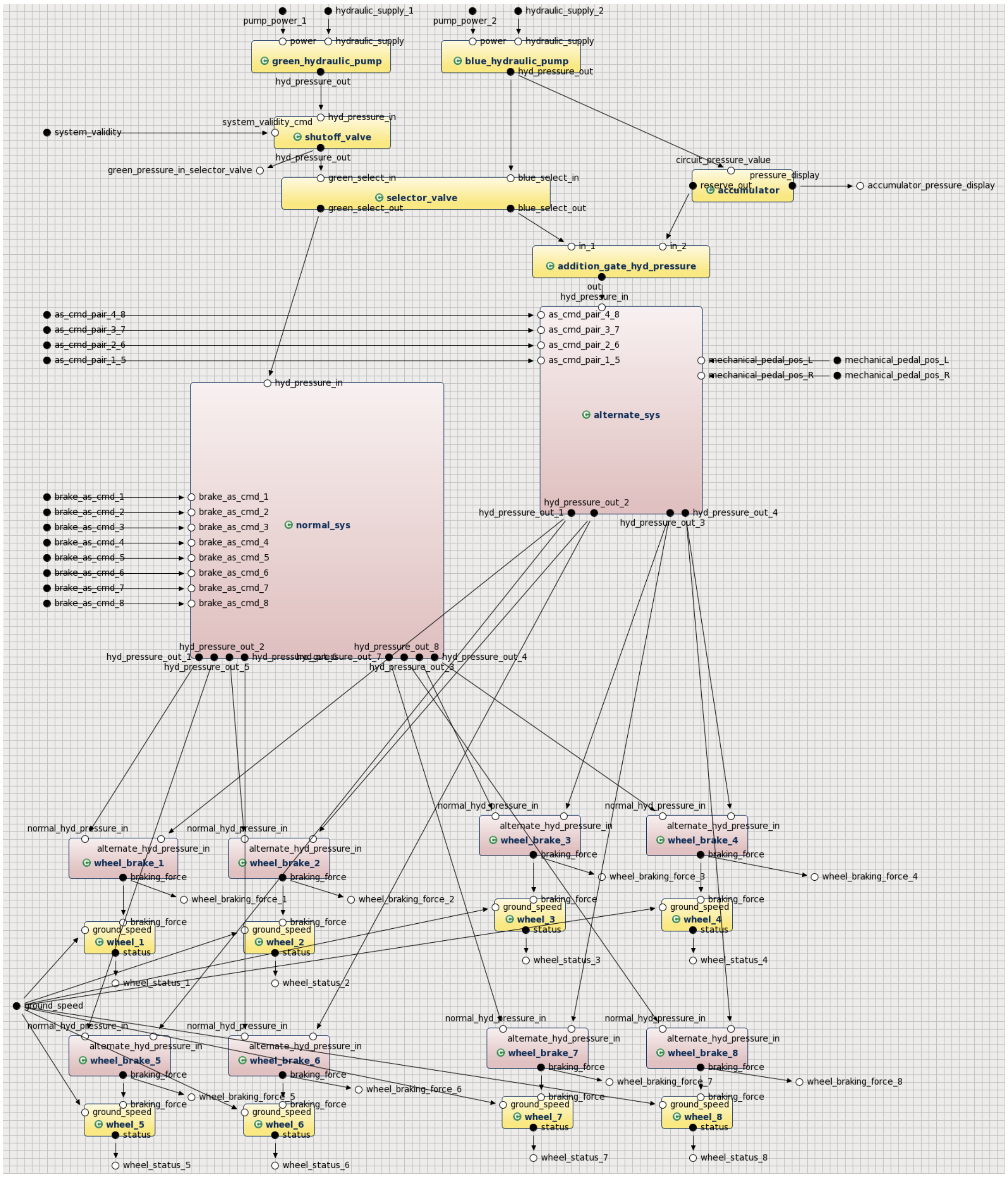


Figure 53: Physical System decomposition

## C.8 Normal Brake System

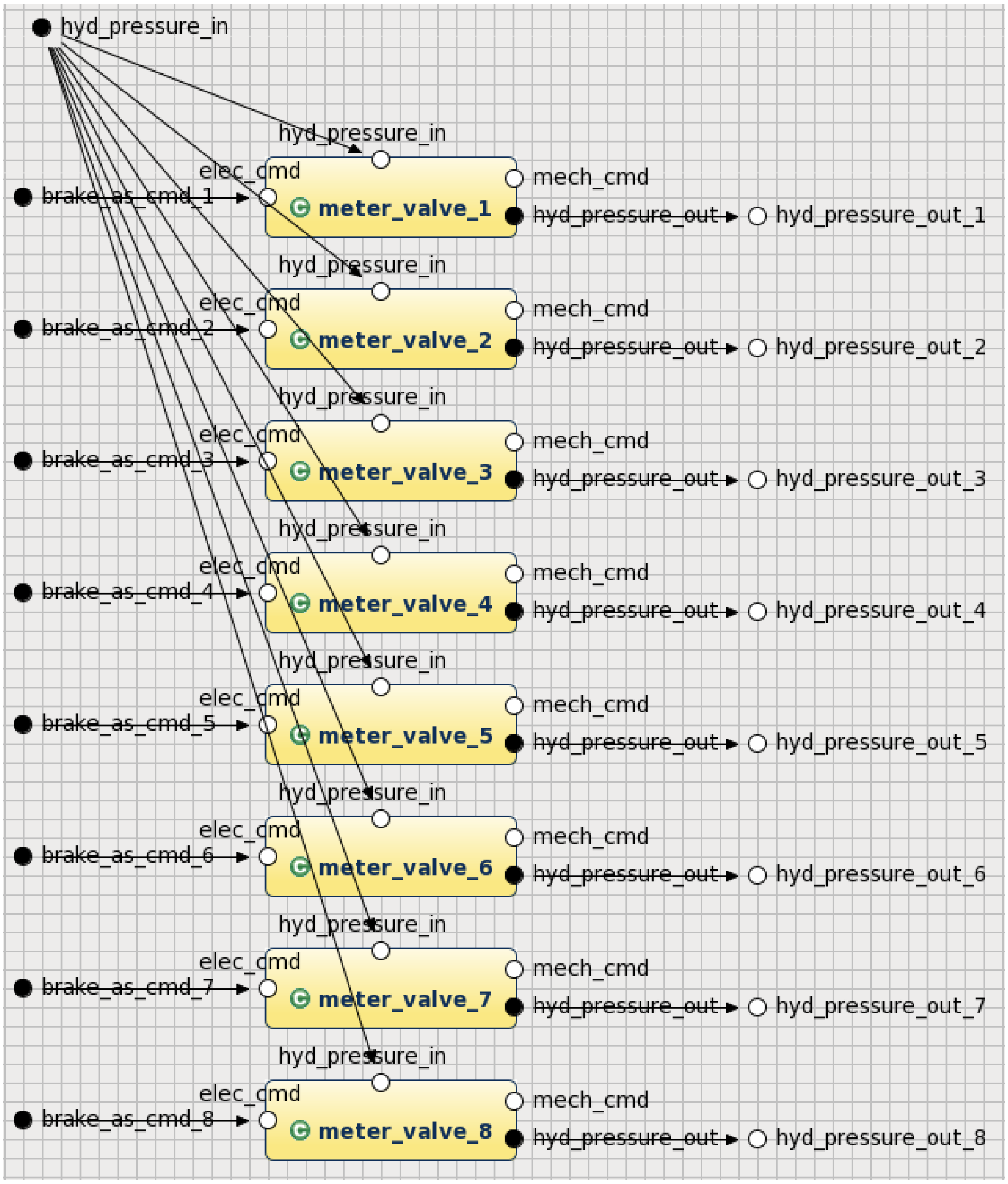


Figure 54: Normal Brake System decomposition

## C.9 Alternate Brake System

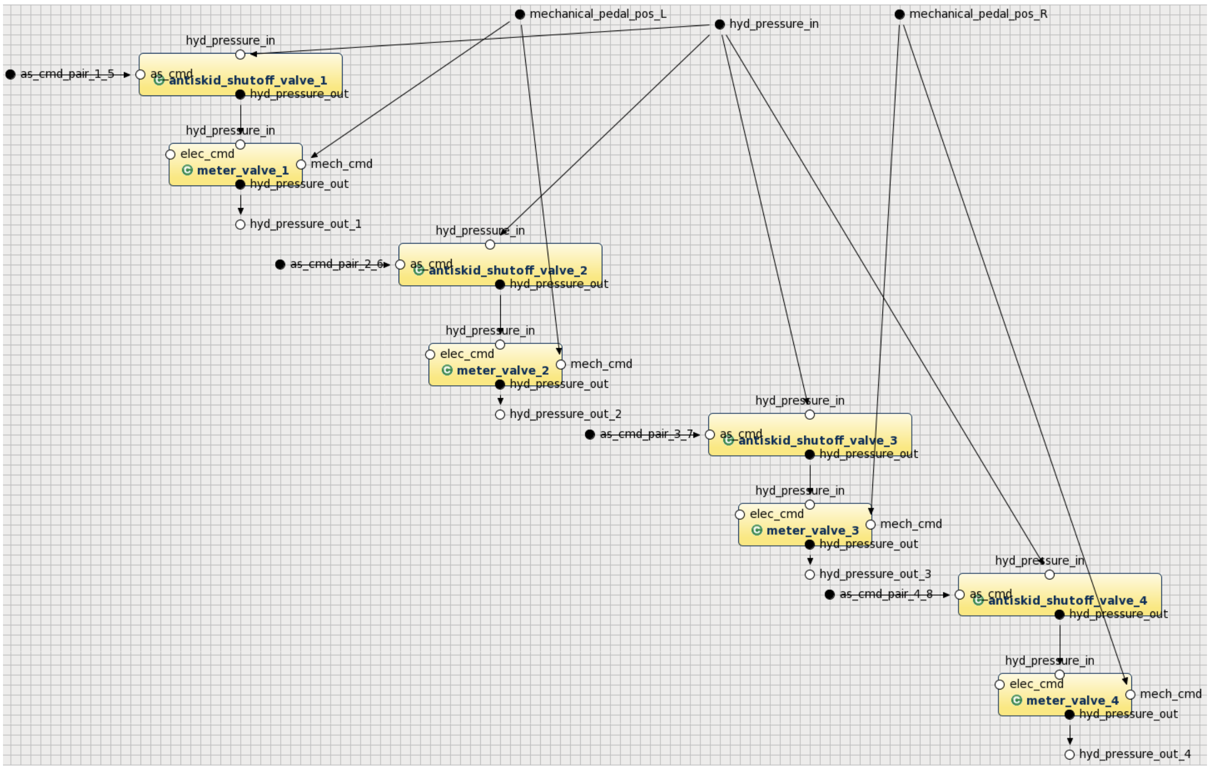


Figure 55: Alternate Brake System decomposition

## C.10 Wheel Brake

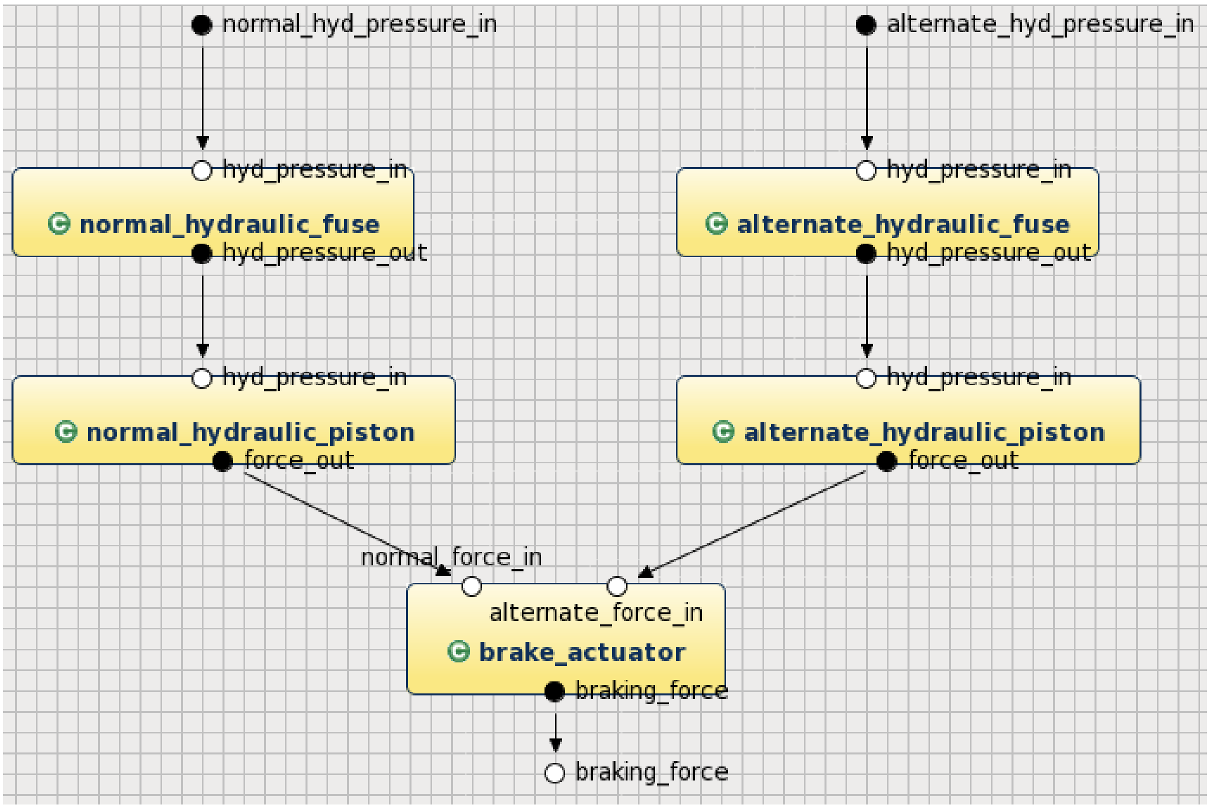


Figure 56: Wheel Brake decomposition

# D WBS Arch2bis architecture decomposition

## D.1 Environment

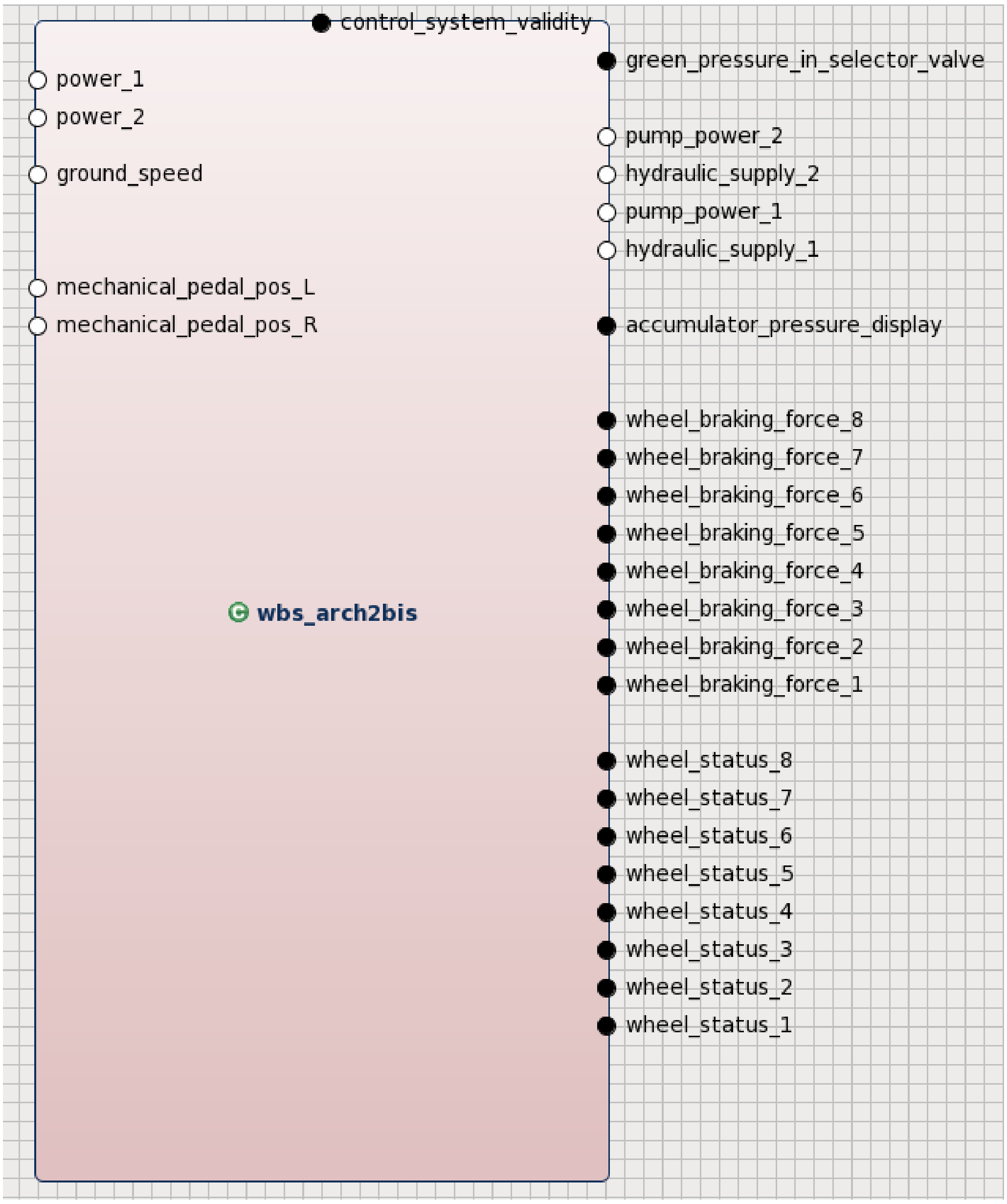


Figure 57: Environment of the Wheel Brake System

## D.2 Wheel Brake System

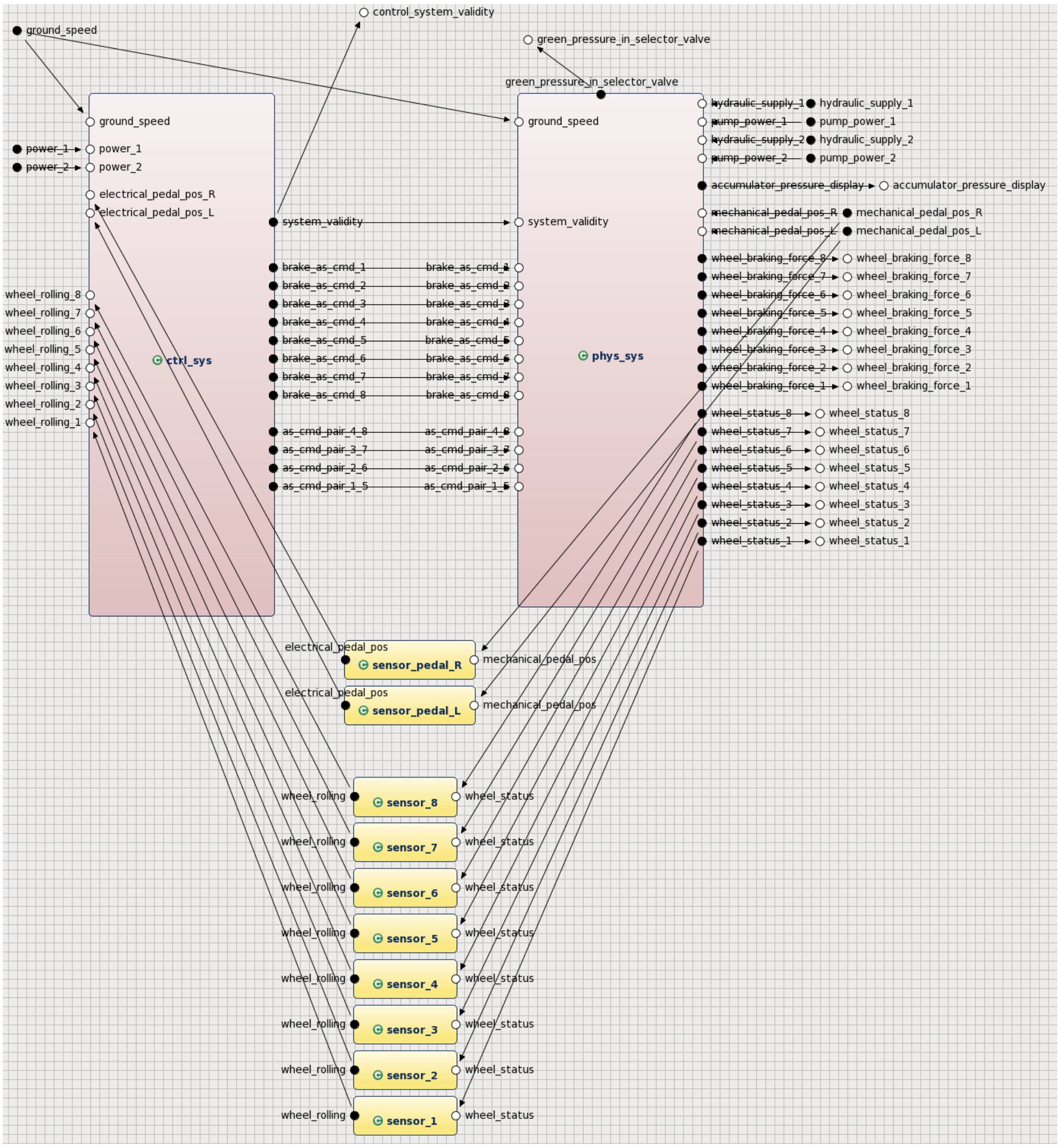


Figure 58: Wheel Brake System decomposition

## D.3 Control System

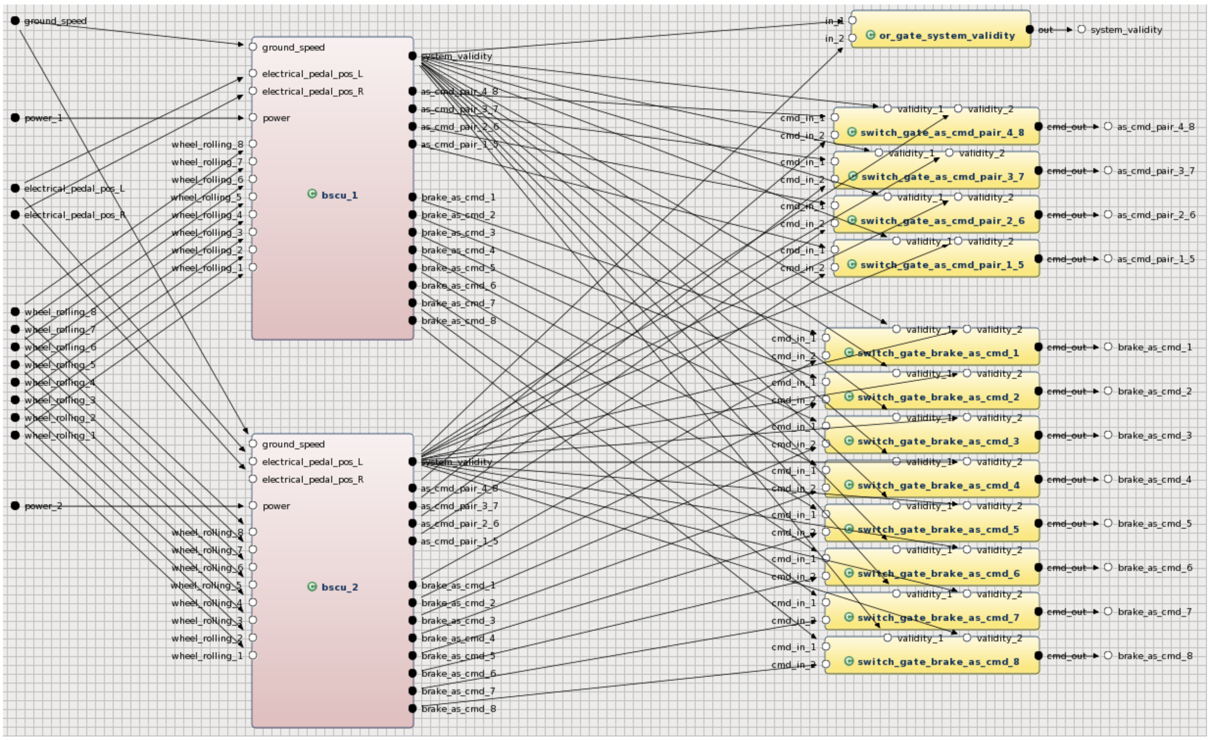


Figure 59: Control System decomposition

## D.4 BSCU

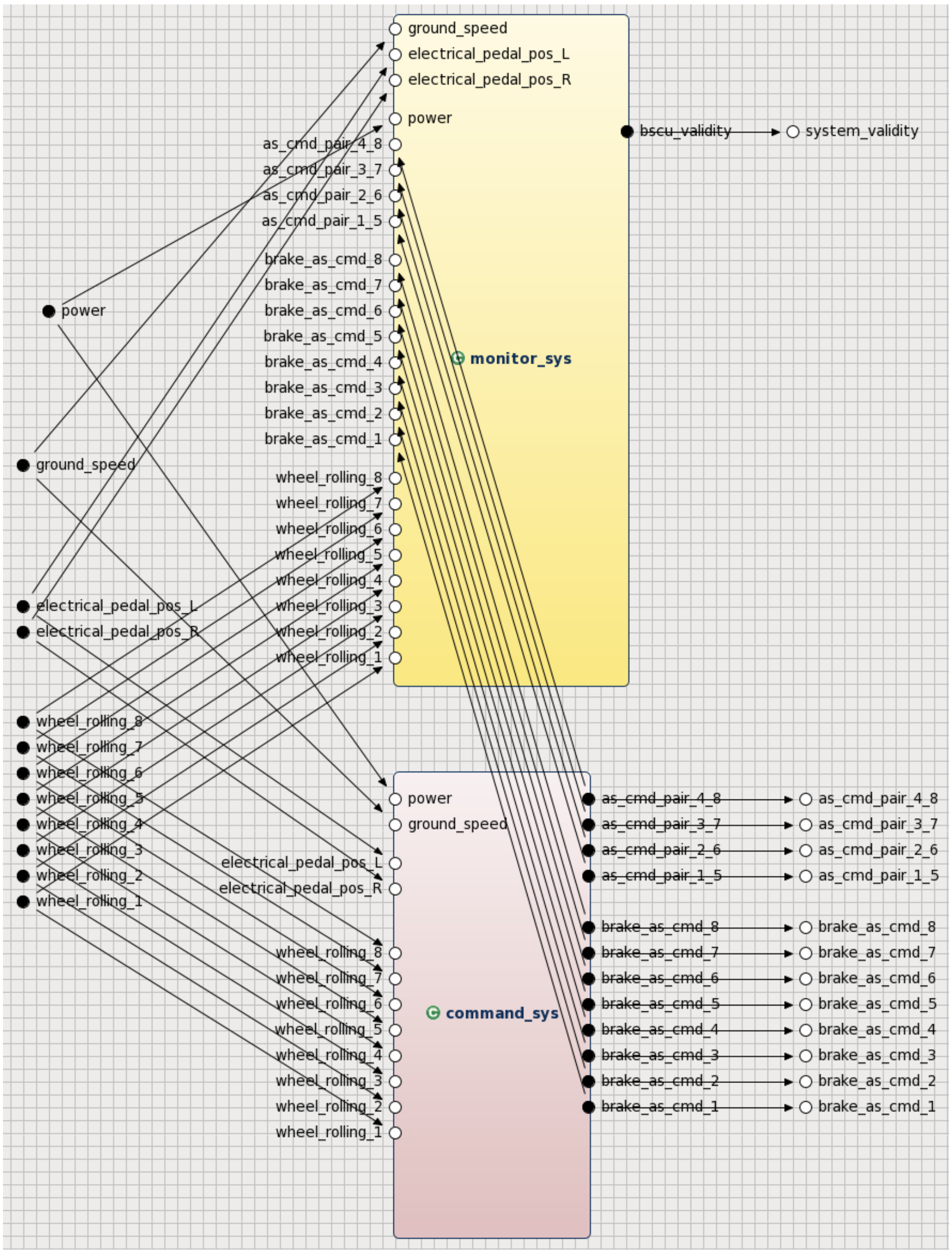


Figure 60: BSCU decomposition

## D.5 Command System

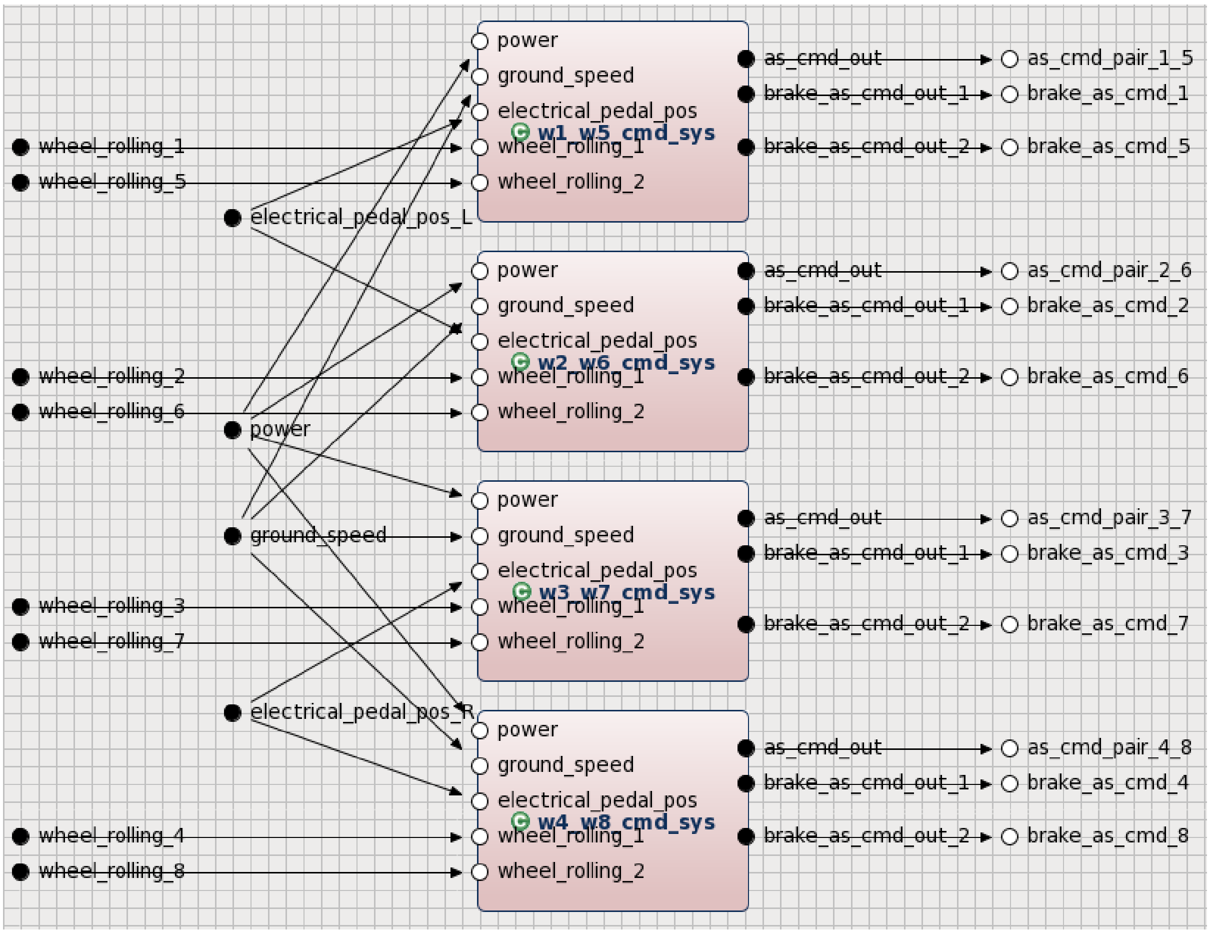


Figure 61: Command System decomposition

## D.6 Wheel Pair Command System

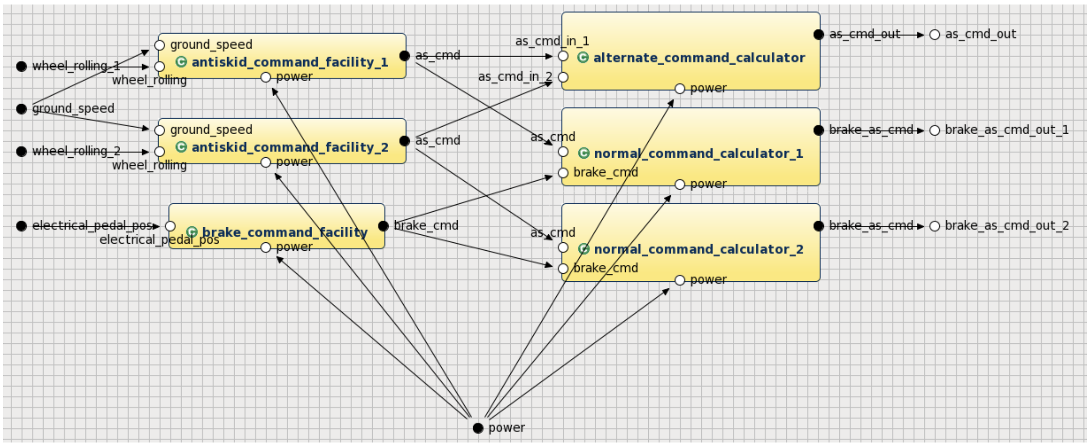


Figure 62: Wheel Pair Command System decomposition

## D.7 Physical System

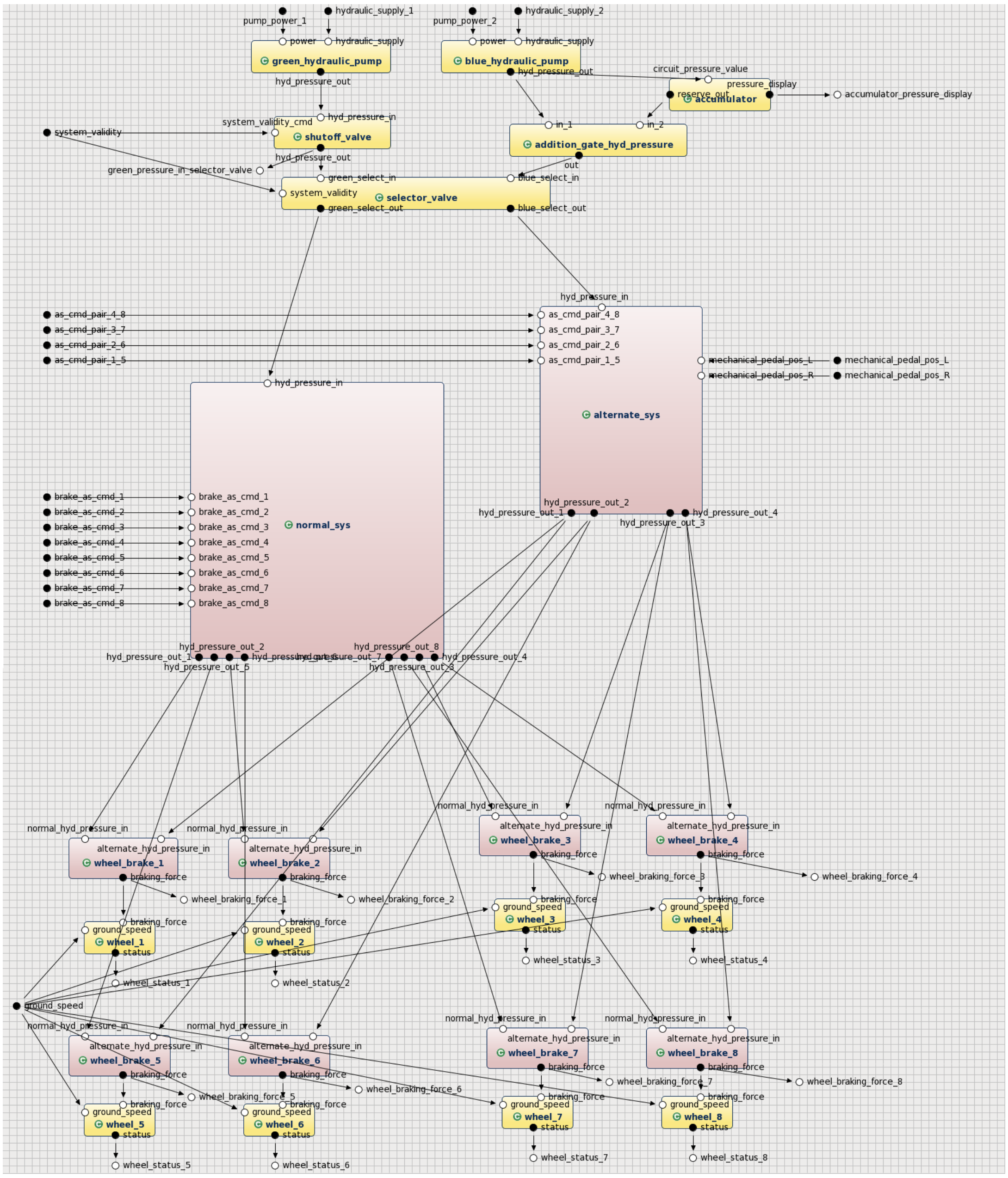


Figure 63: Physical System decomposition

## D.8 Normal Brake System

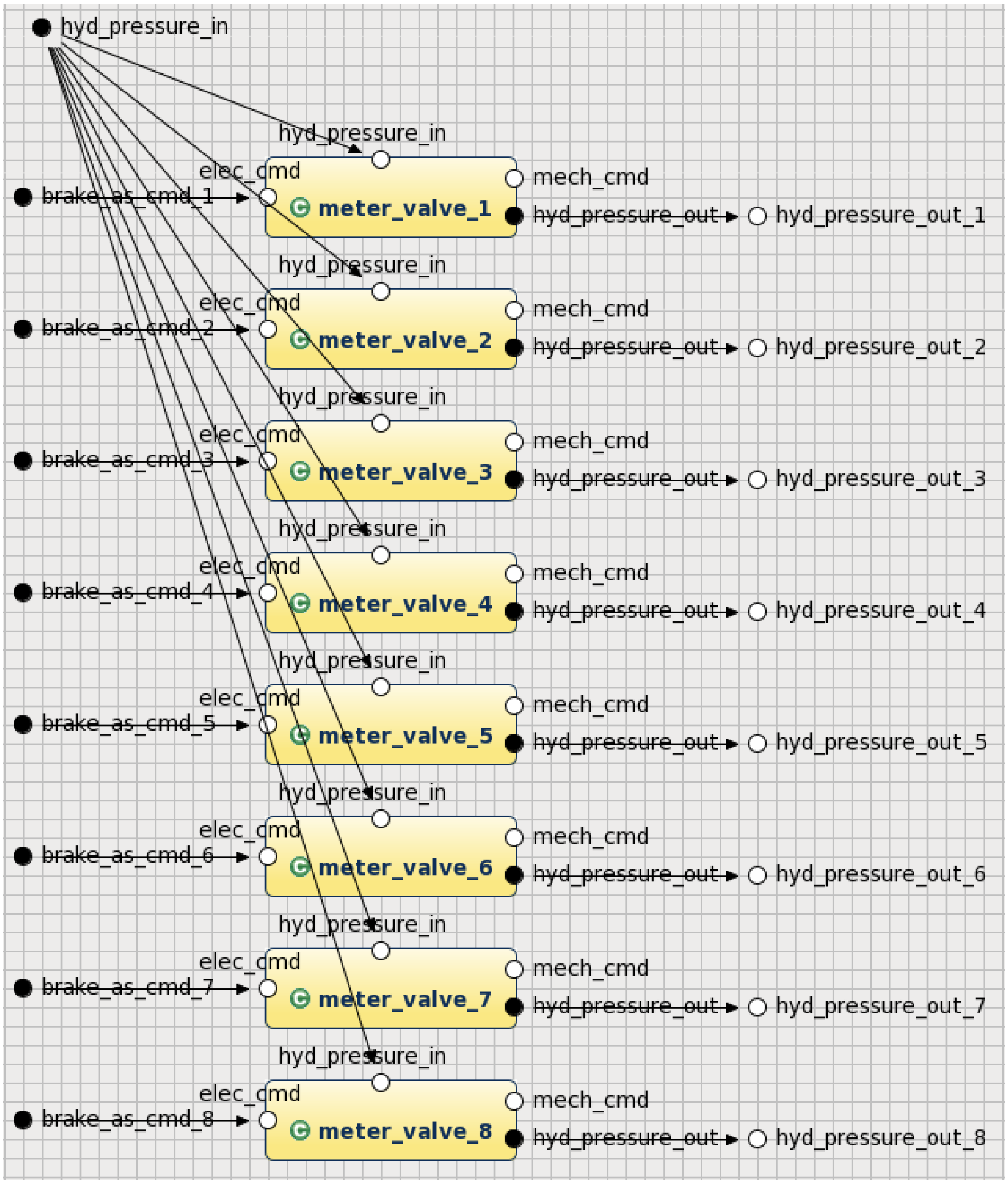


Figure 64: Normal Brake System decomposition

## D.9 Alternate Brake System

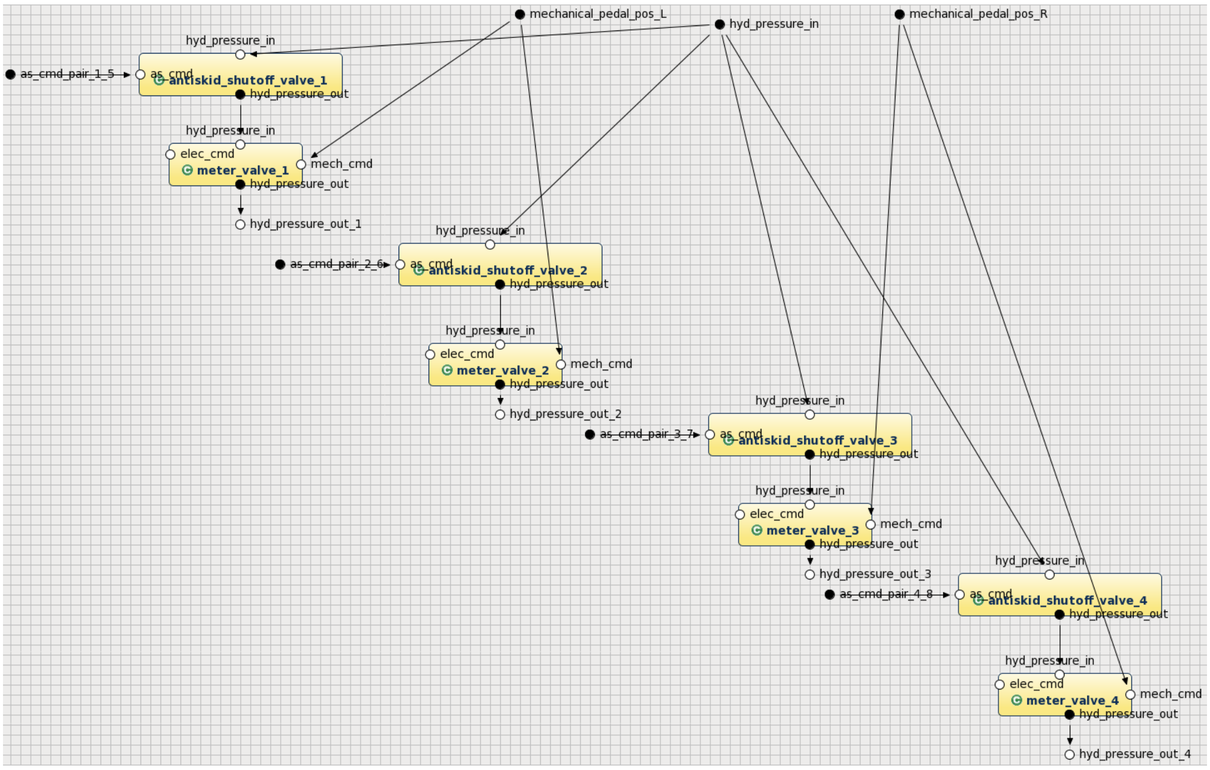


Figure 65: Alternate Brake System decomposition

## D.10 Wheel Brake

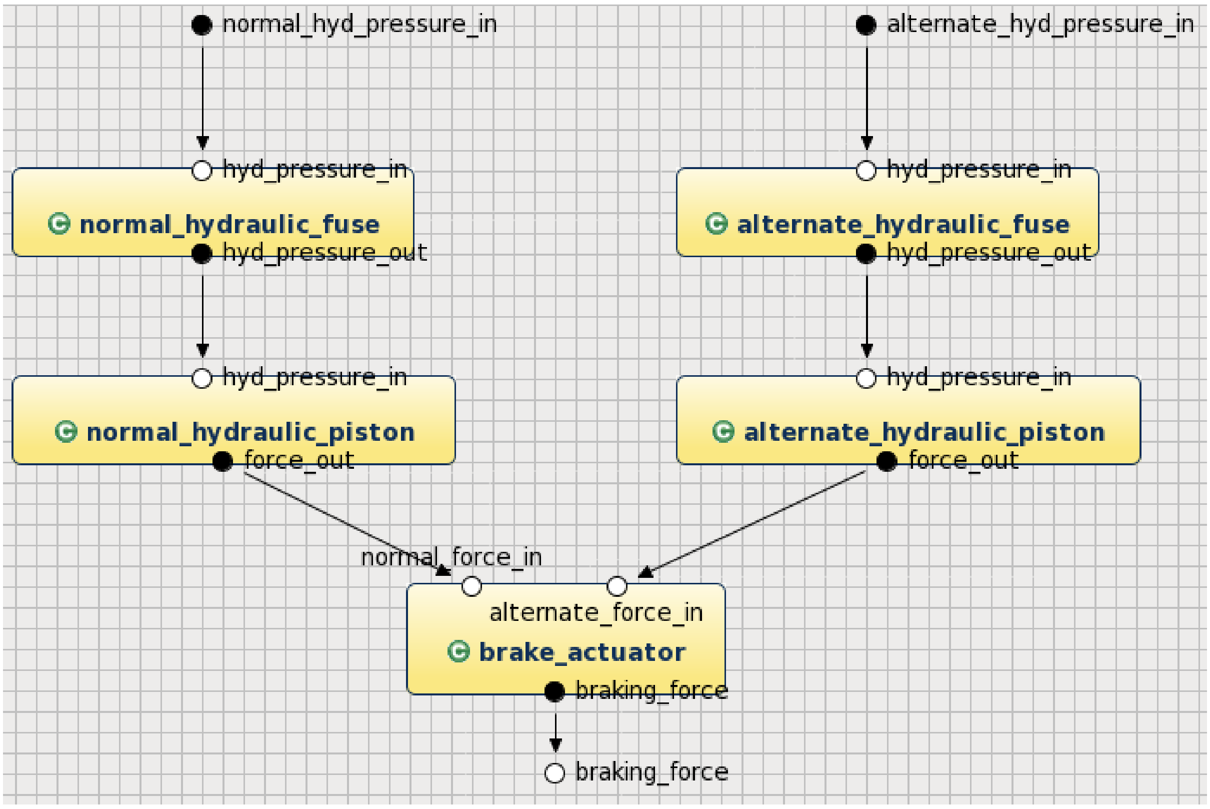


Figure 66: Wheel Brake decomposition

# E WBS Arch3 architecture decomposition

## E.1 Environment

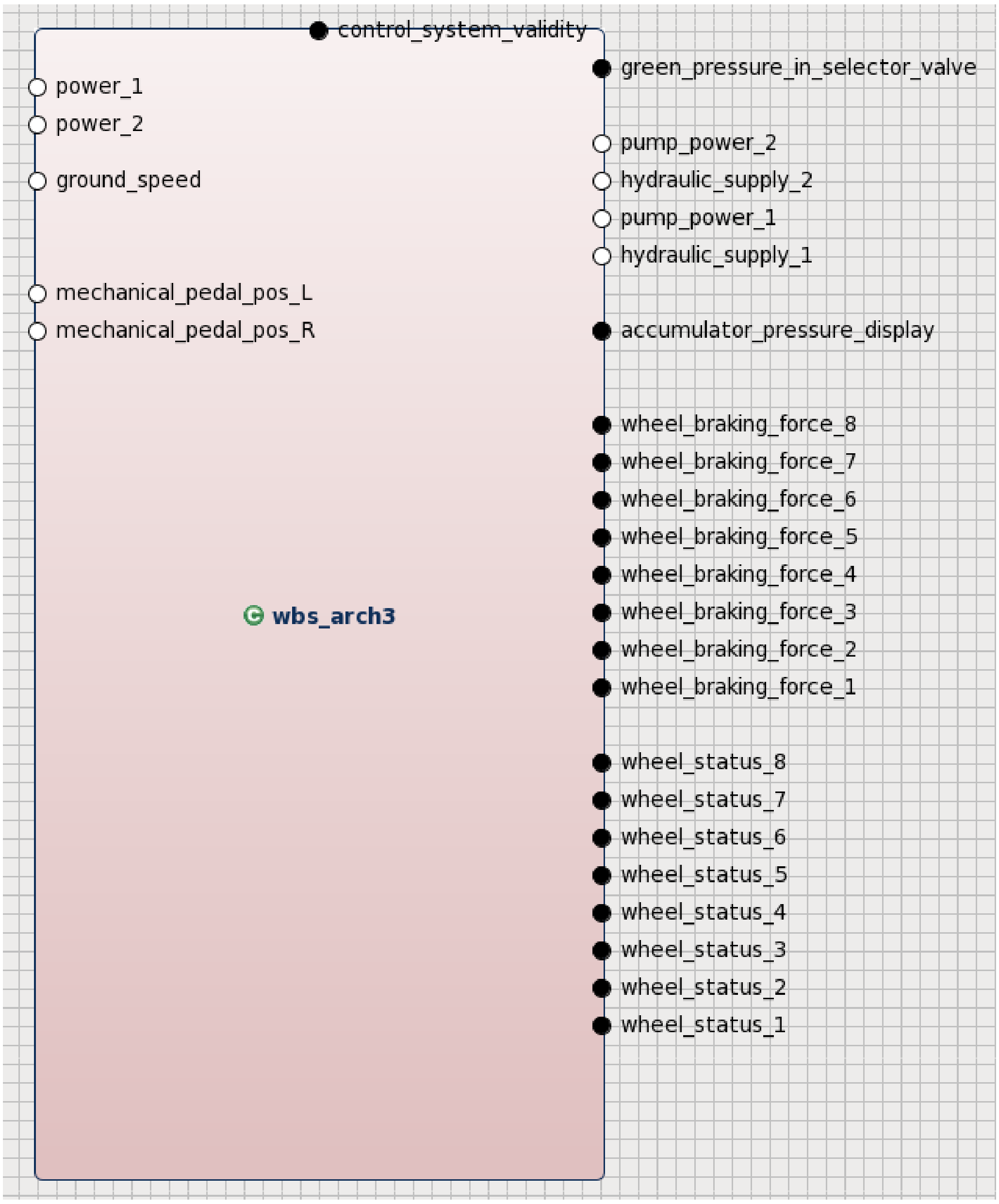


Figure 67: Environment of the Wheel Brake System

## E.2 Wheel Brake System

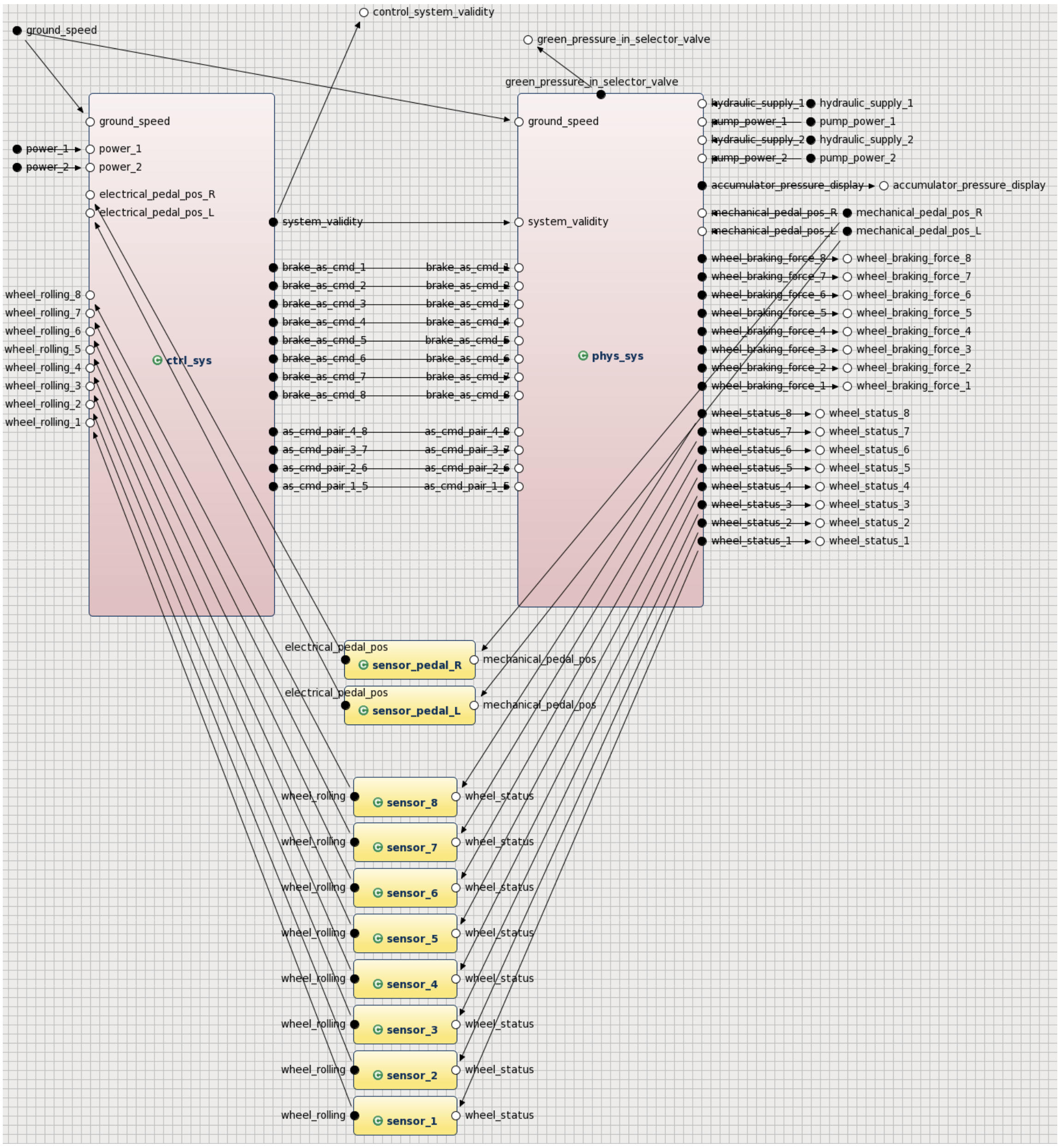


Figure 68: Wheel Brake System decomposition

## E.3 Control System

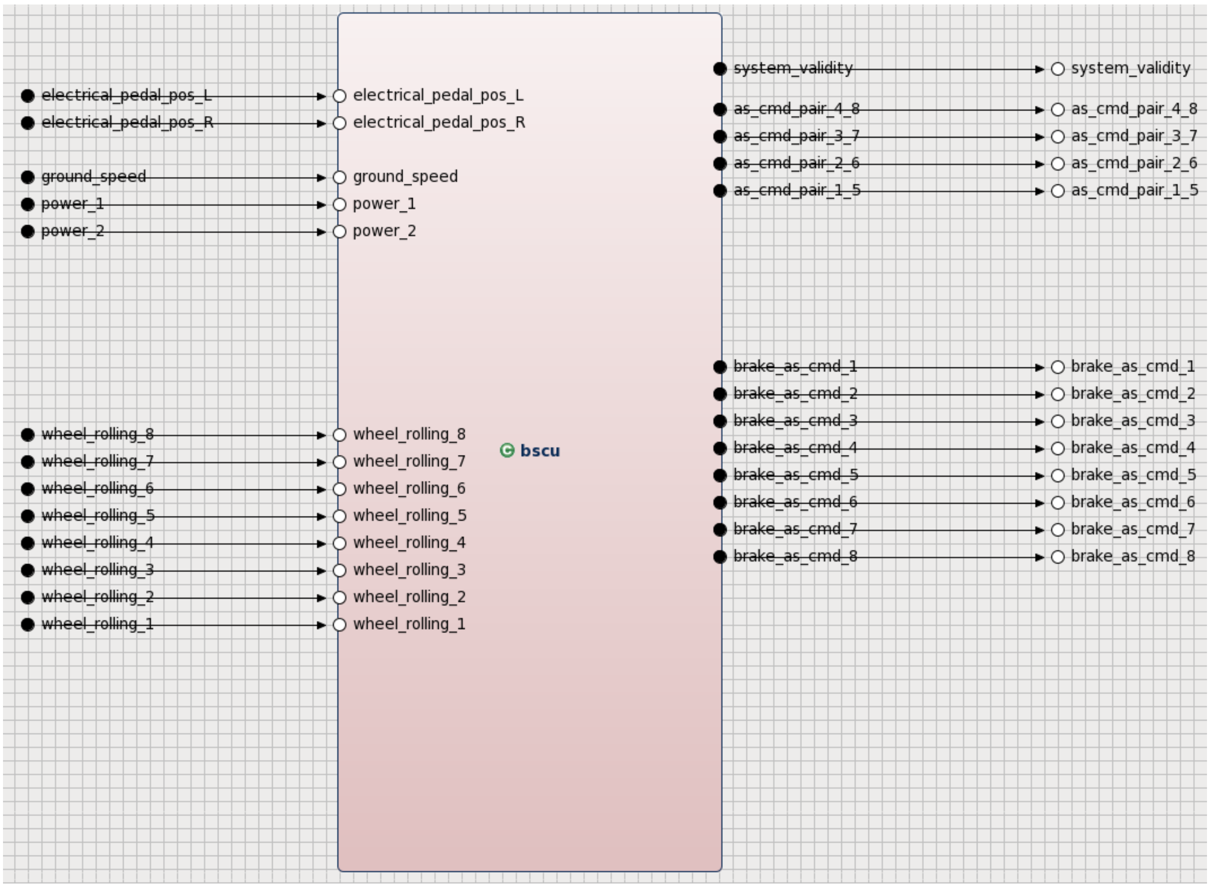


Figure 69: Control System decomposition

## E.4 BSCU

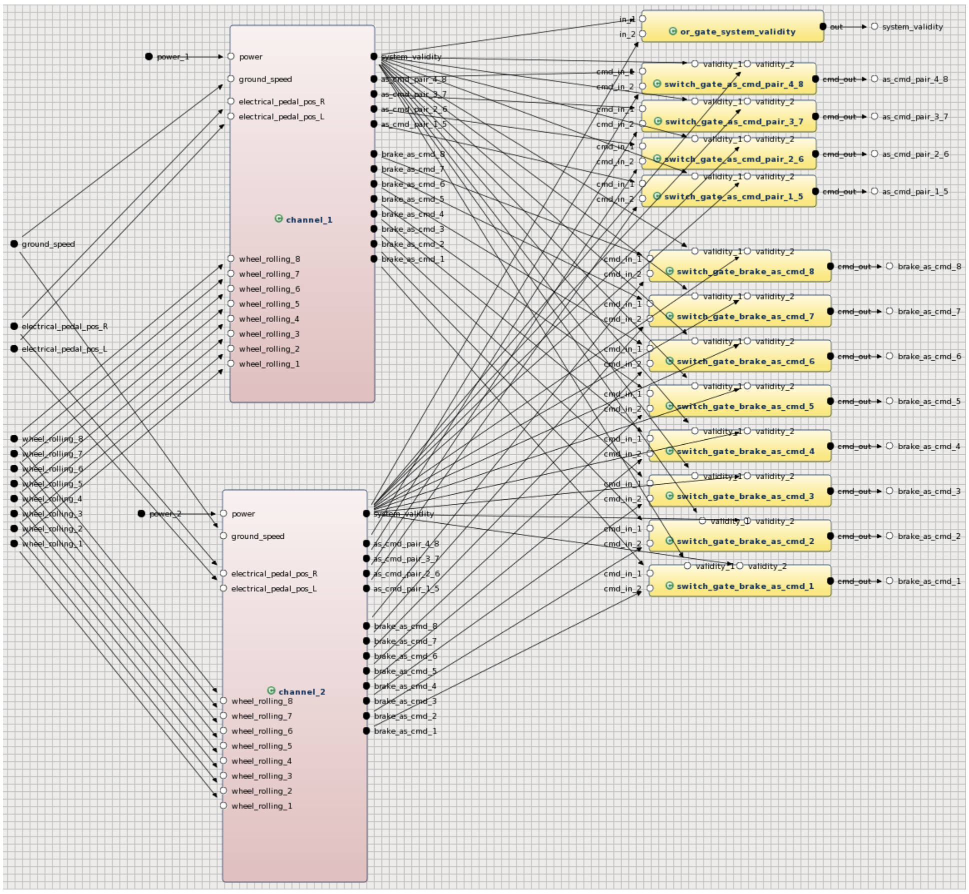


Figure 70: BSCU decomposition

## E.5 Channel

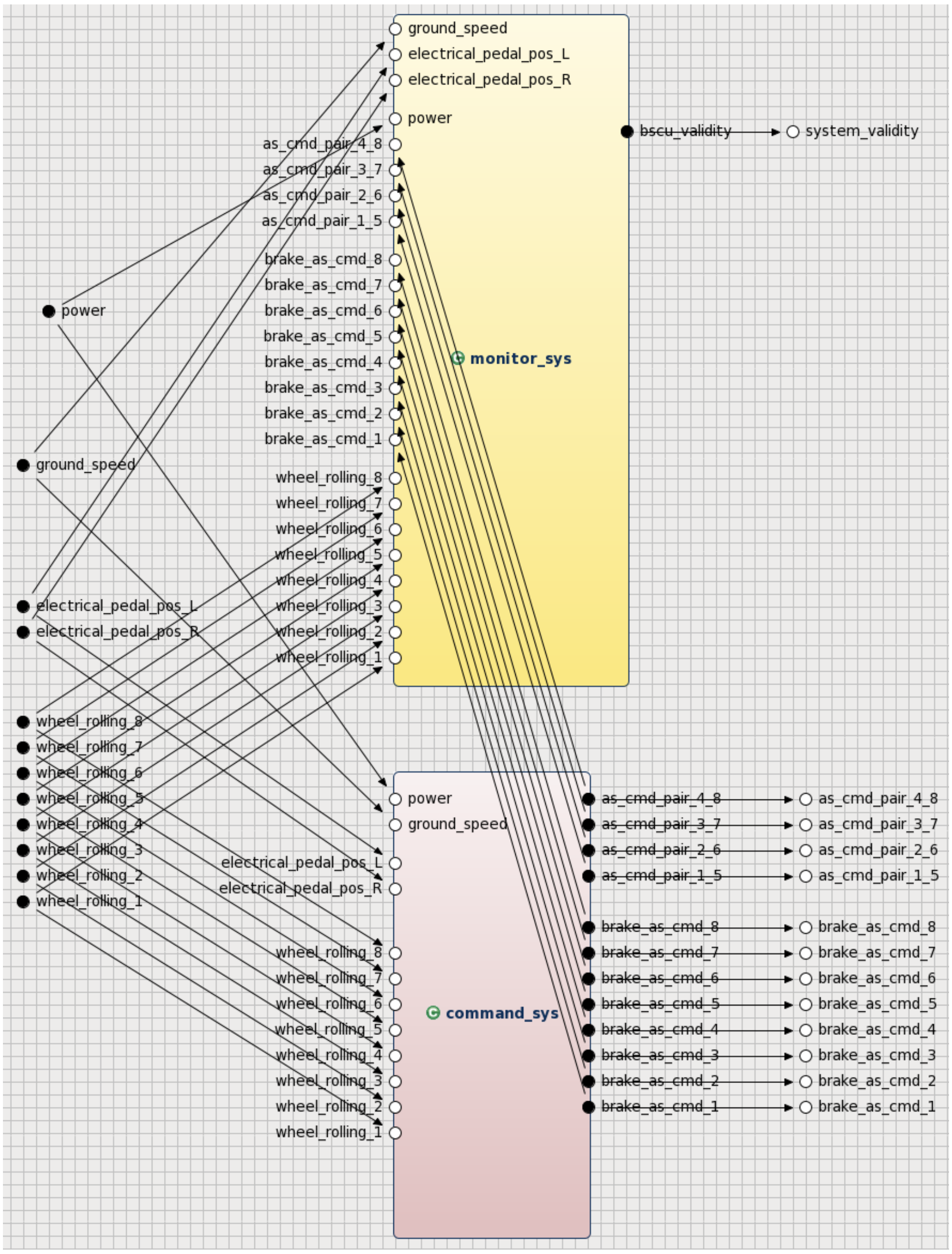


Figure 71: Channel decomposition

## E.6 Command System

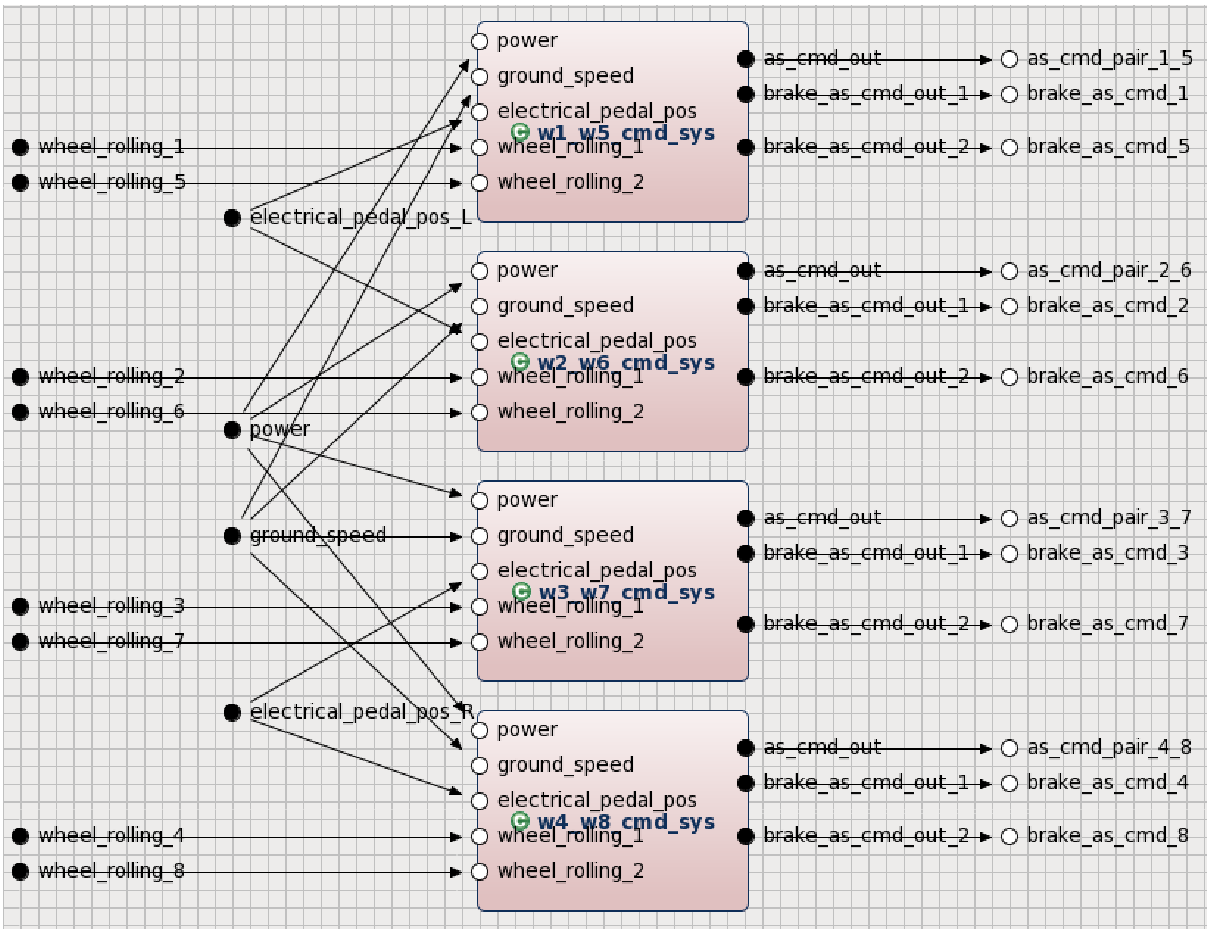


Figure 72: Command System decomposition

## E.7 Wheel Pair Command System

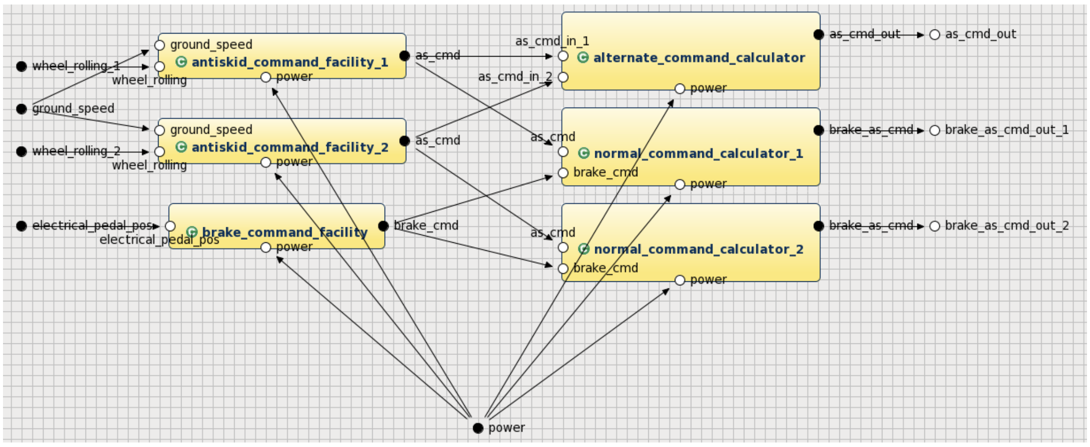


Figure 73: Wheel Pair Command System decomposition

## E.8 Physical System

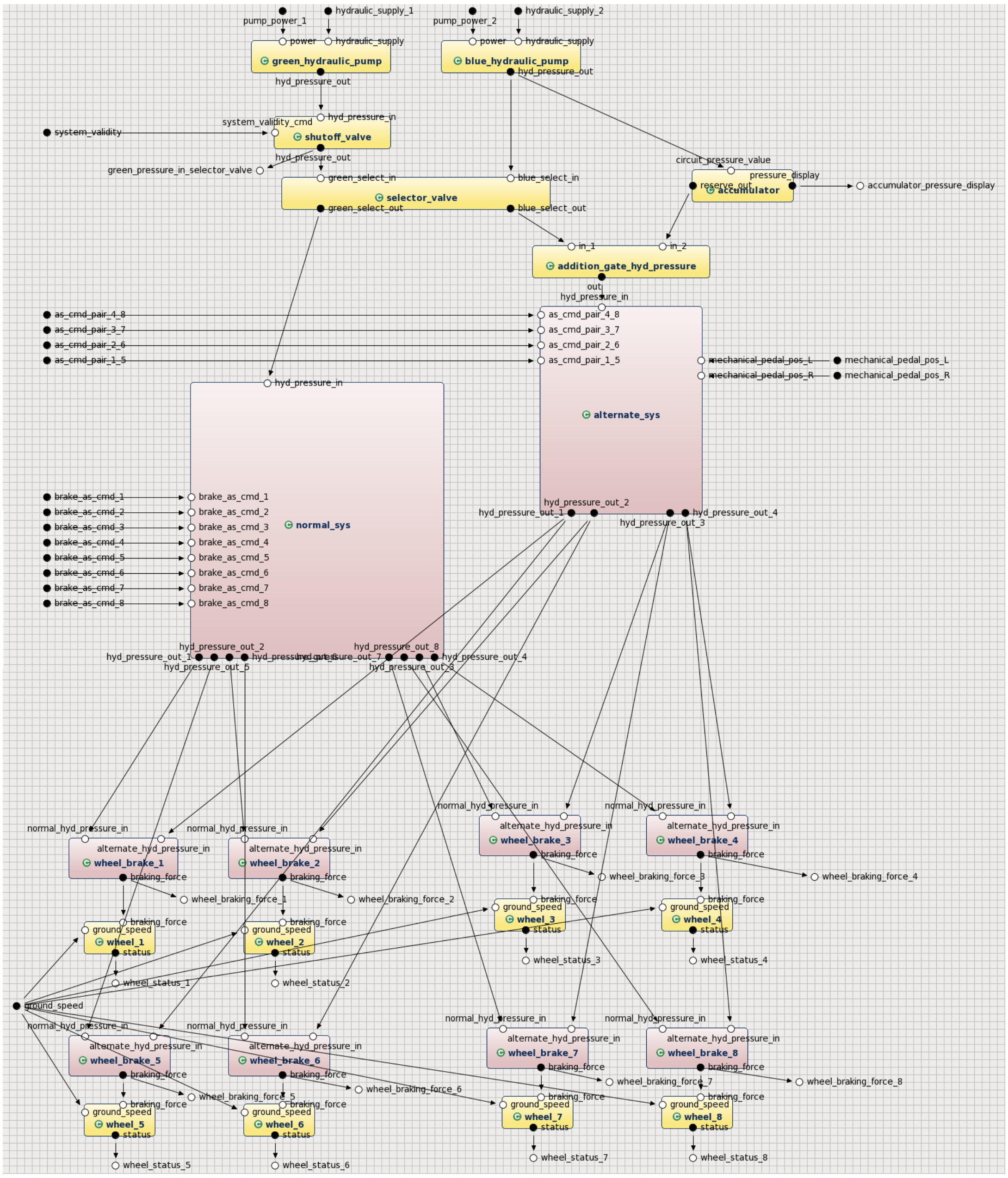


Figure 74: Physical System decomposition

## E.9 Normal Brake System

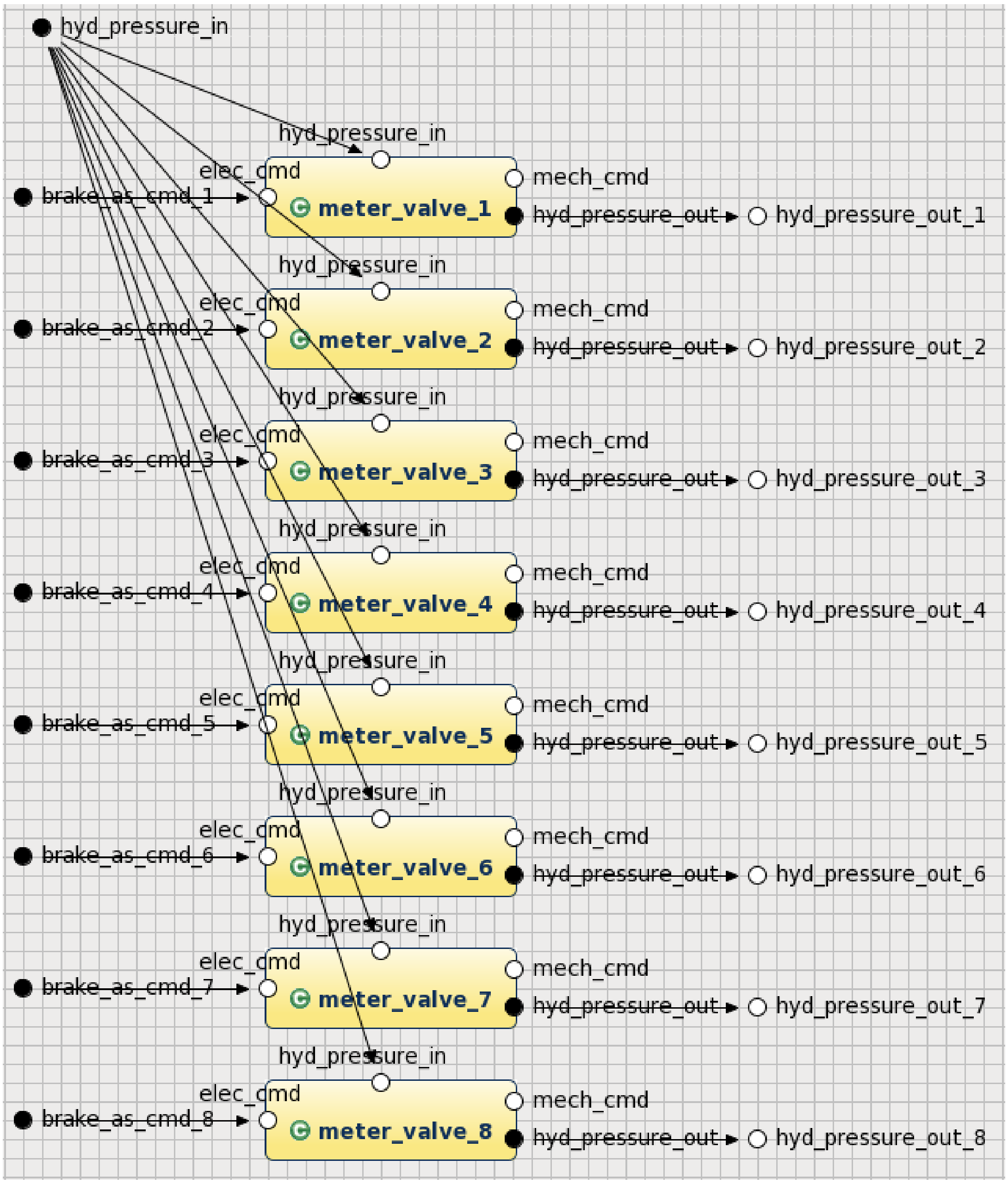


Figure 75: Normal Brake System decomposition

## E.10 Alternate Brake System

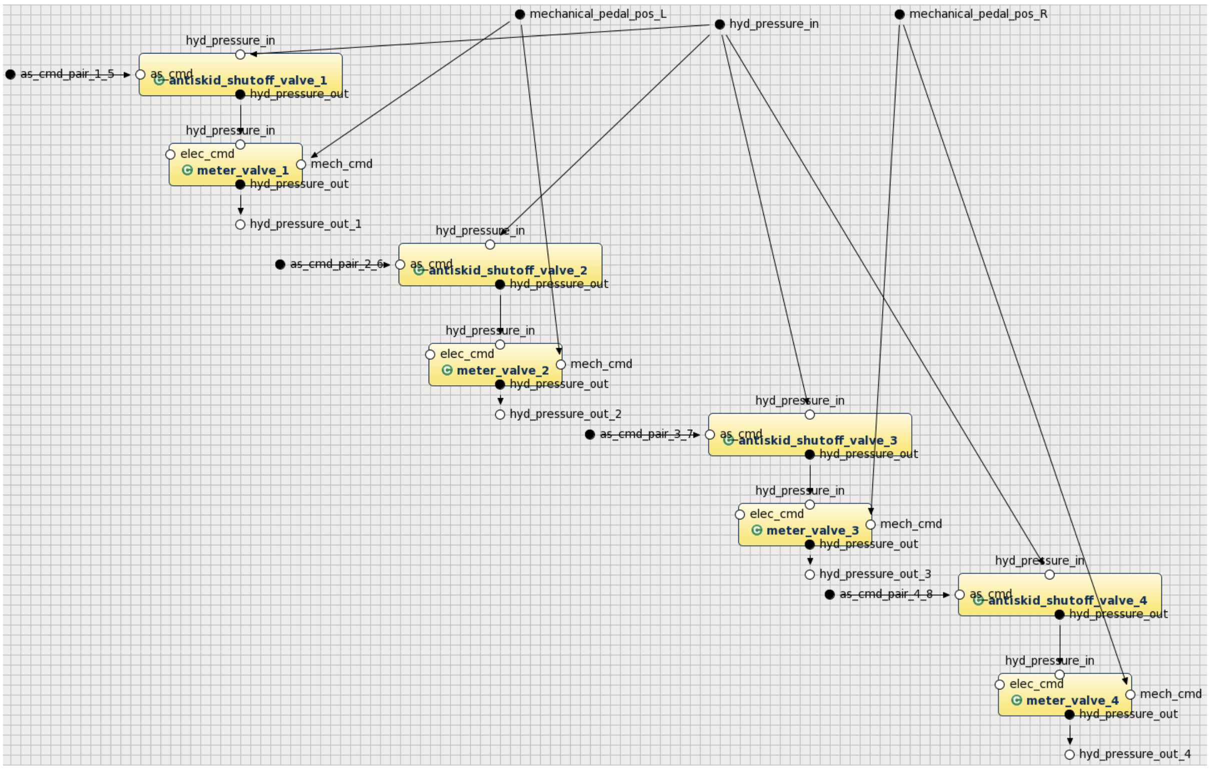


Figure 76: Alternate Brake System decomposition

## E.11 Wheel Brake

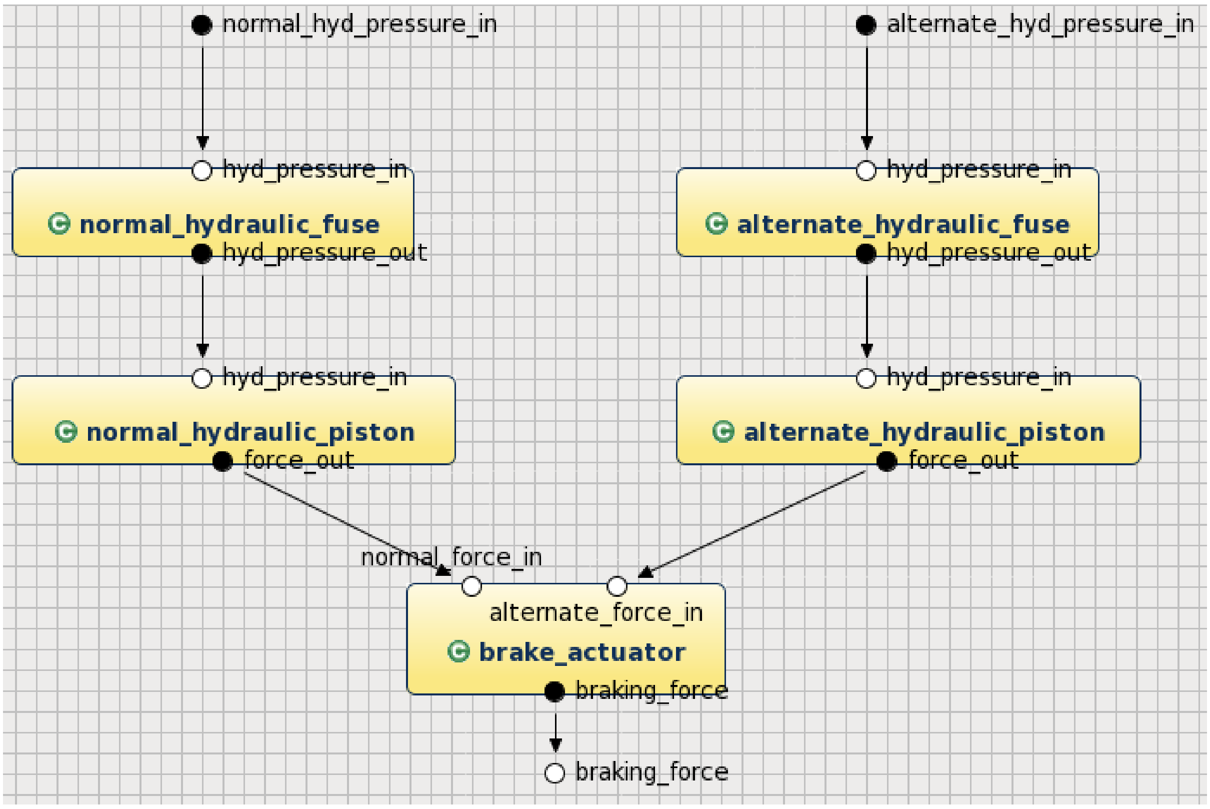


Figure 77: Wheel Brake decomposition

# F WBS Arch4 architecture decomposition

## F.1 Environment

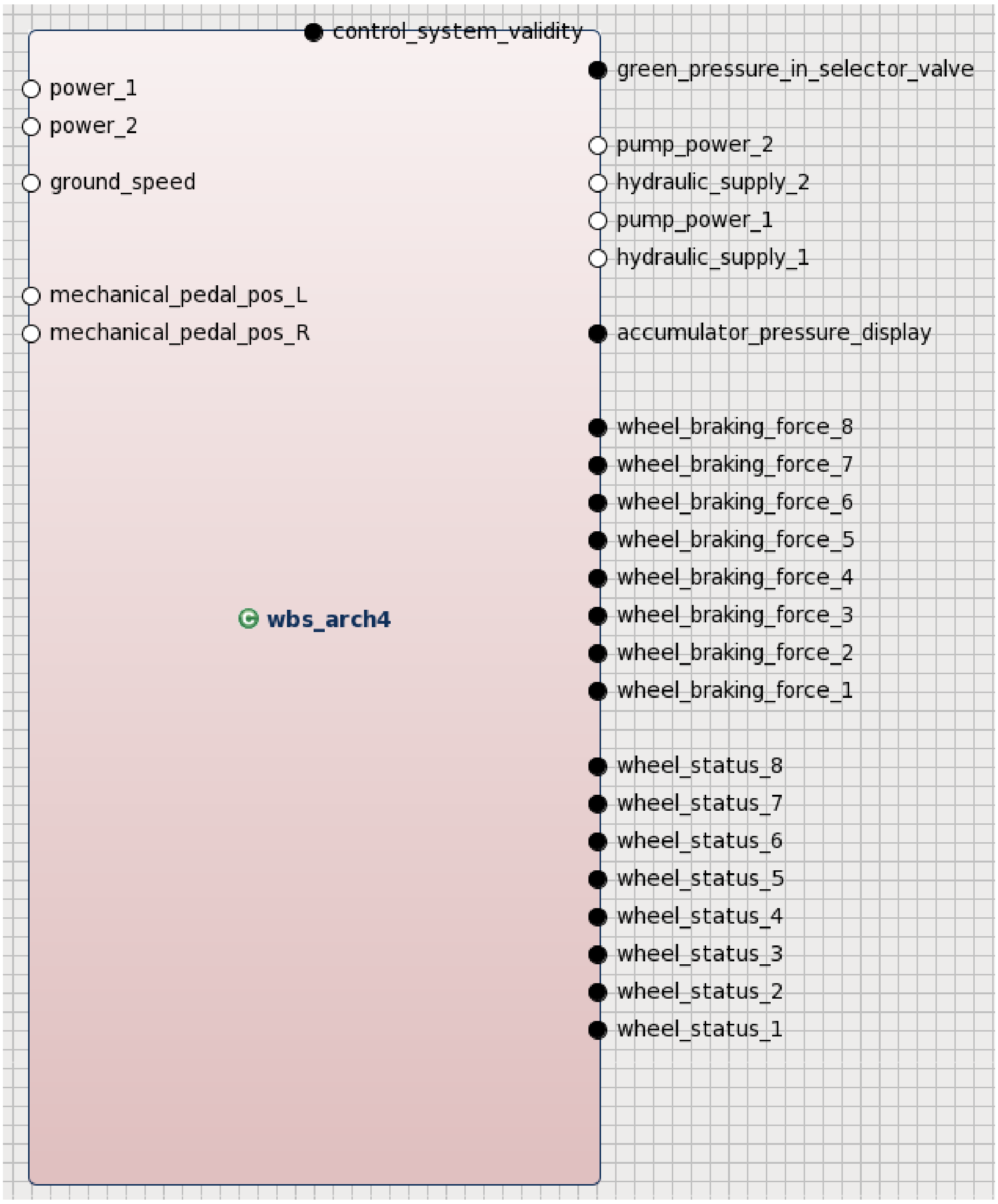


Figure 78: Environment of the Wheel Brake System

## F.2 Wheel Brake System

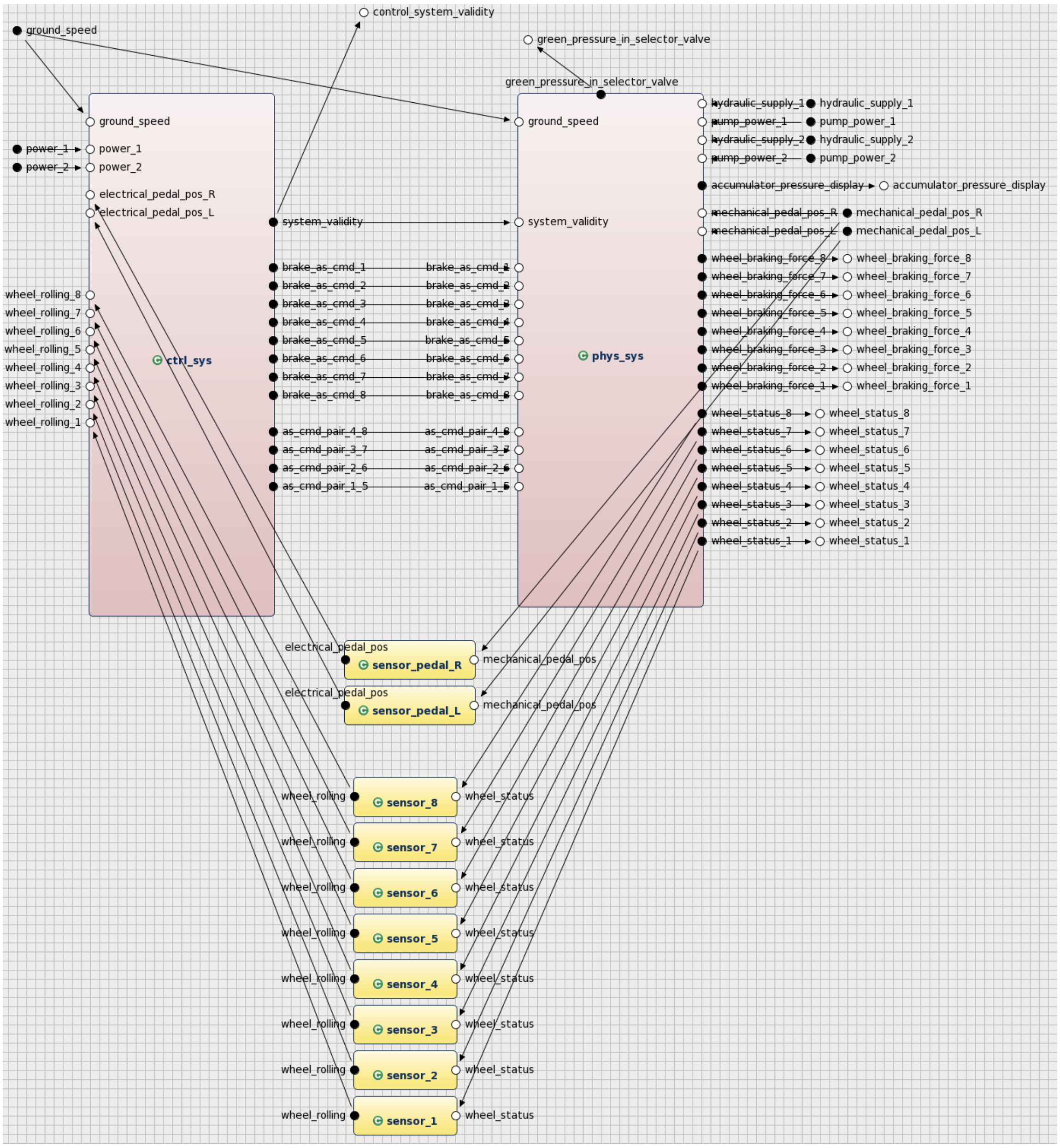


Figure 79: Wheel Brake System decomposition

## F.3 Control System

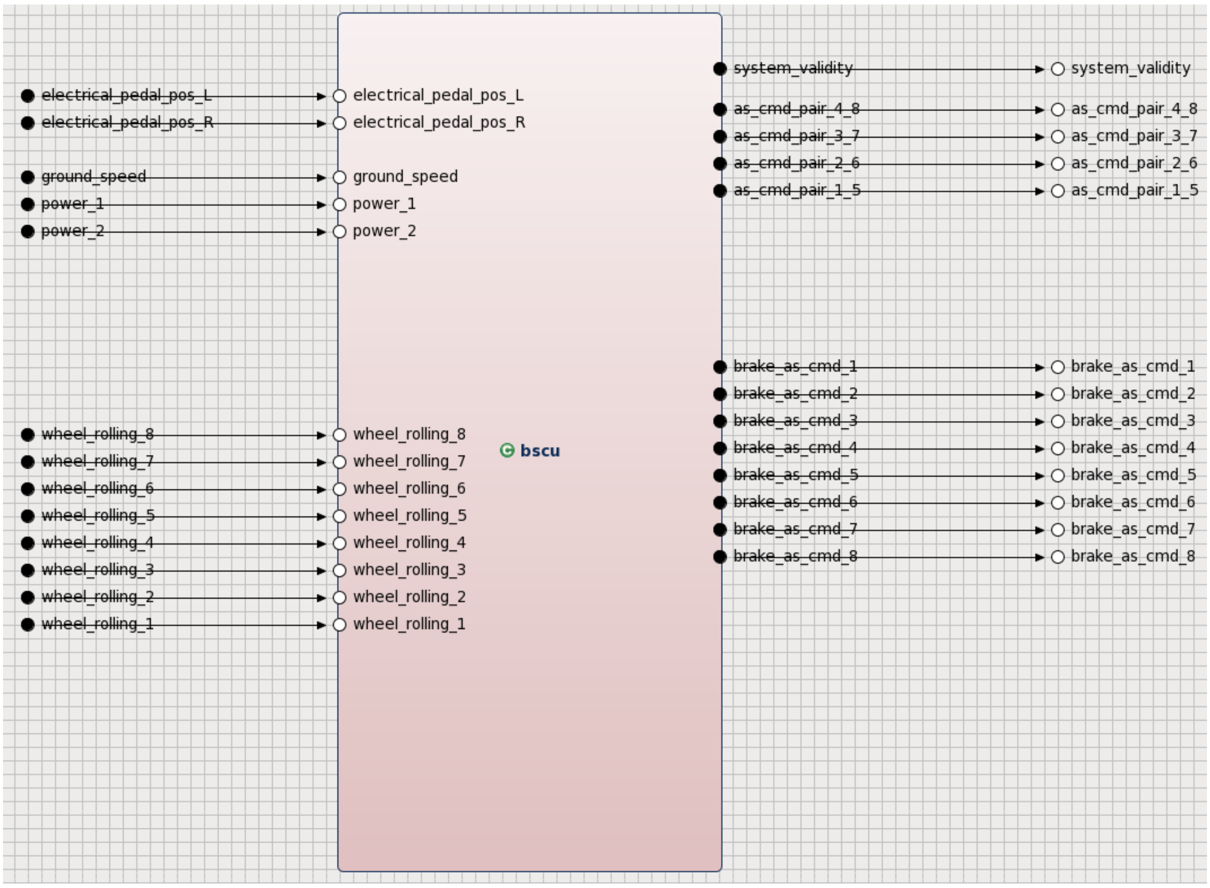


Figure 80: Control System decomposition

## F.4 BSCU

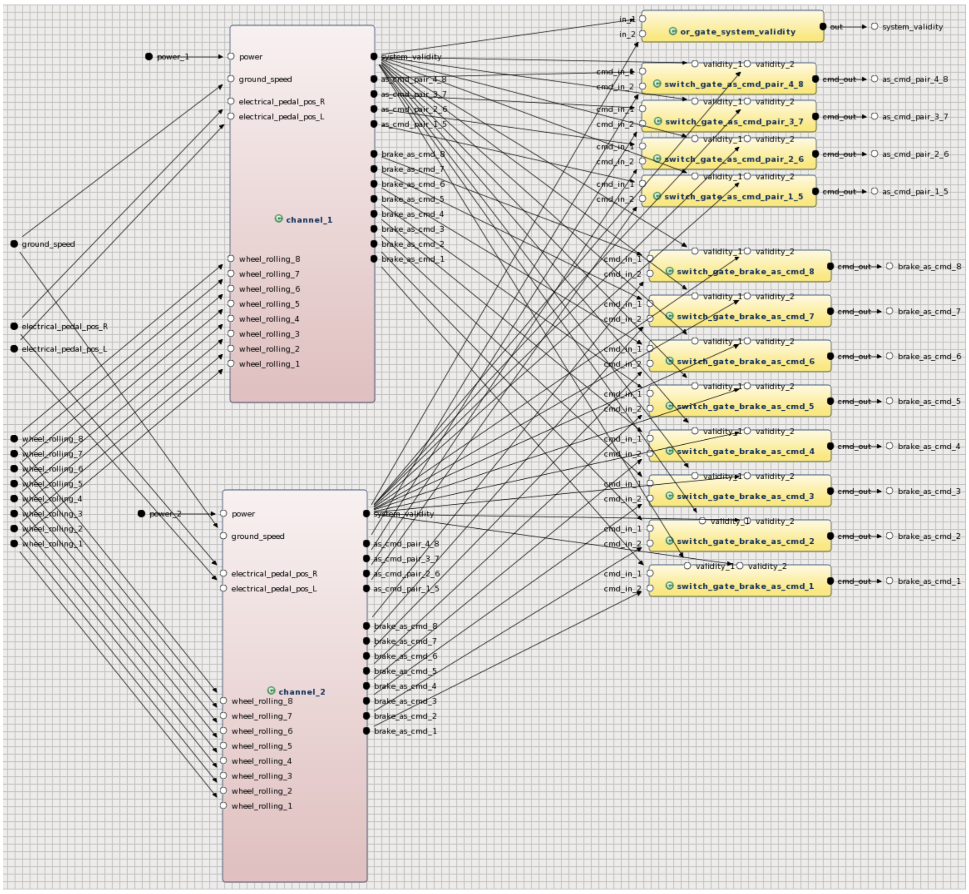


Figure 81: BSCU decomposition

## F.5 Channel

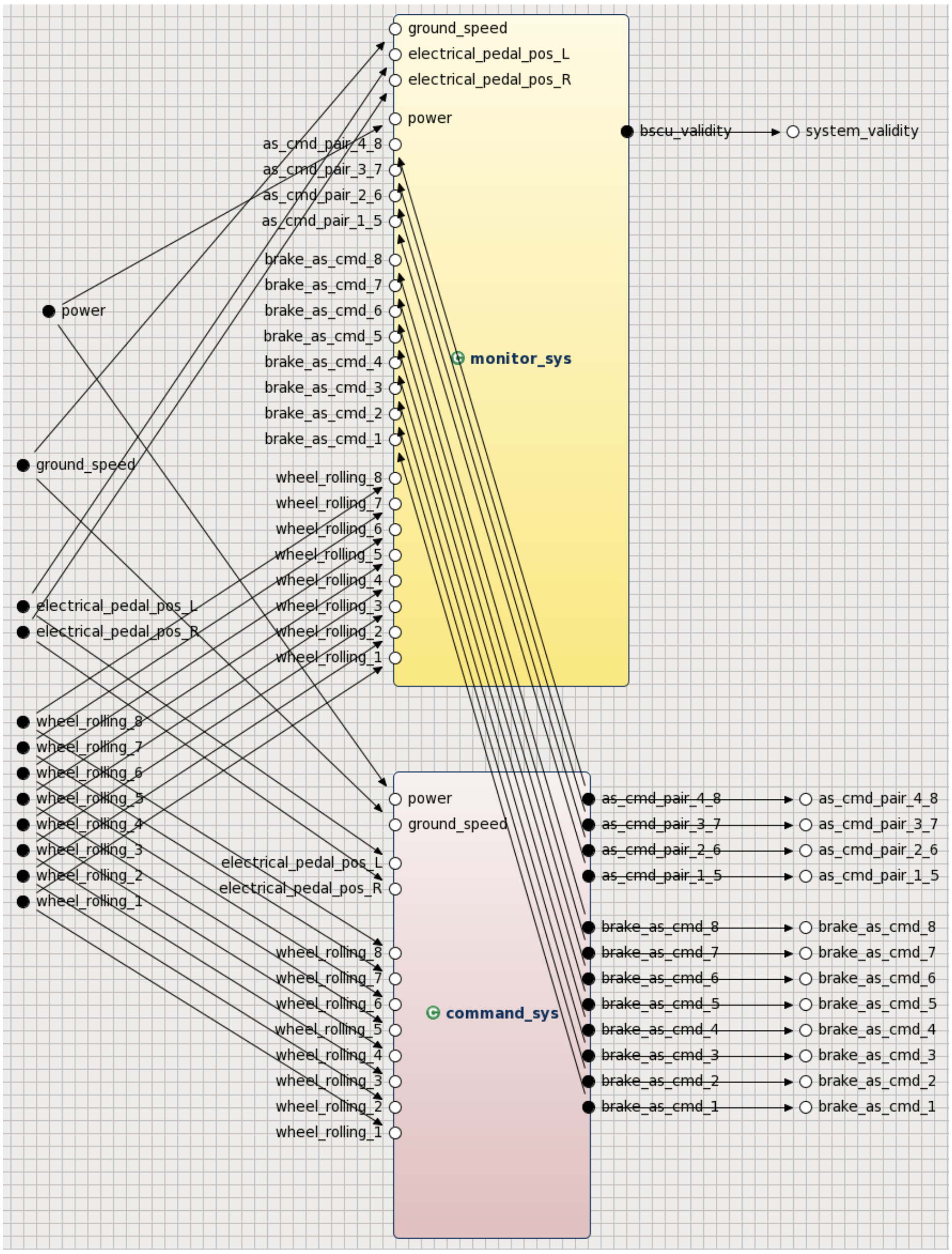


Figure 82: Channel decomposition

## F.6 Command System

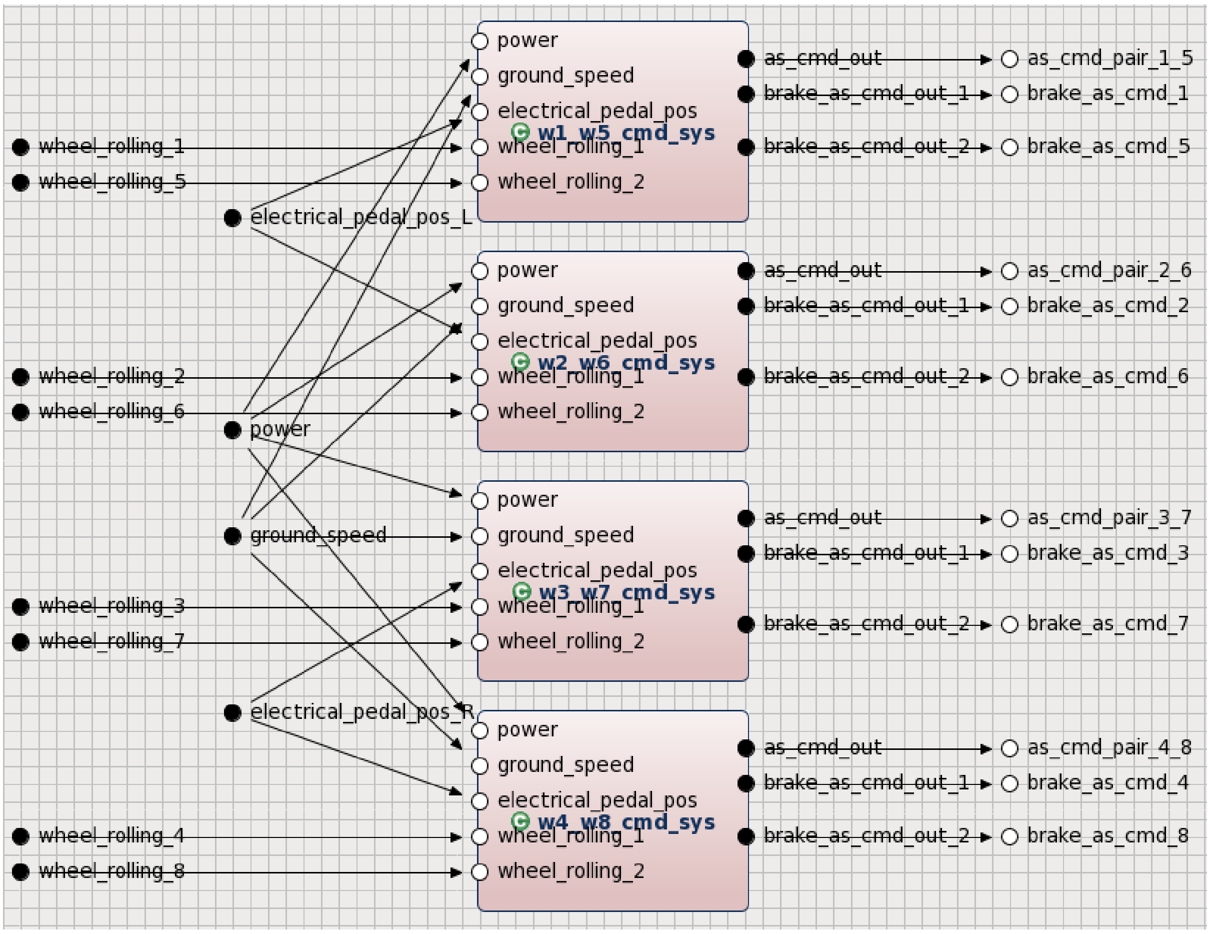


Figure 83: Command System decomposition

## F.7 Wheel Pair Command System

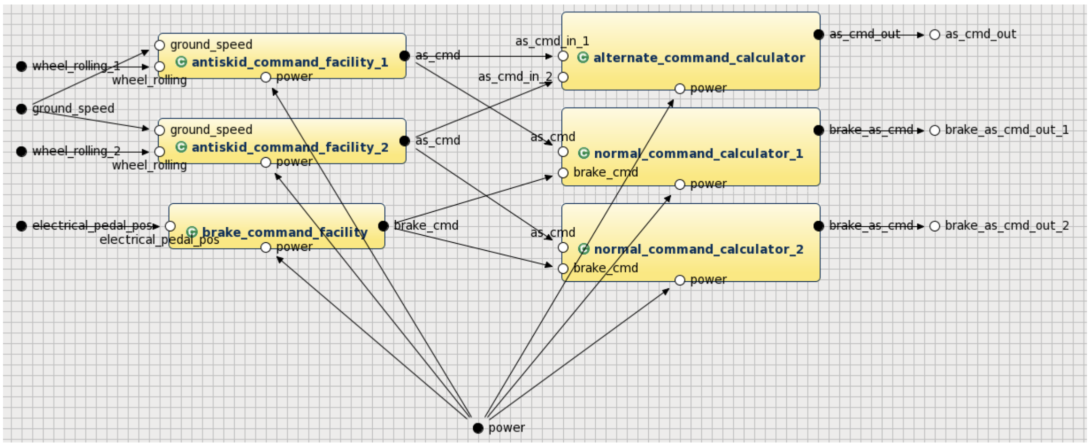


Figure 84: Wheel Pair Command System decomposition

## F.8 Physical System

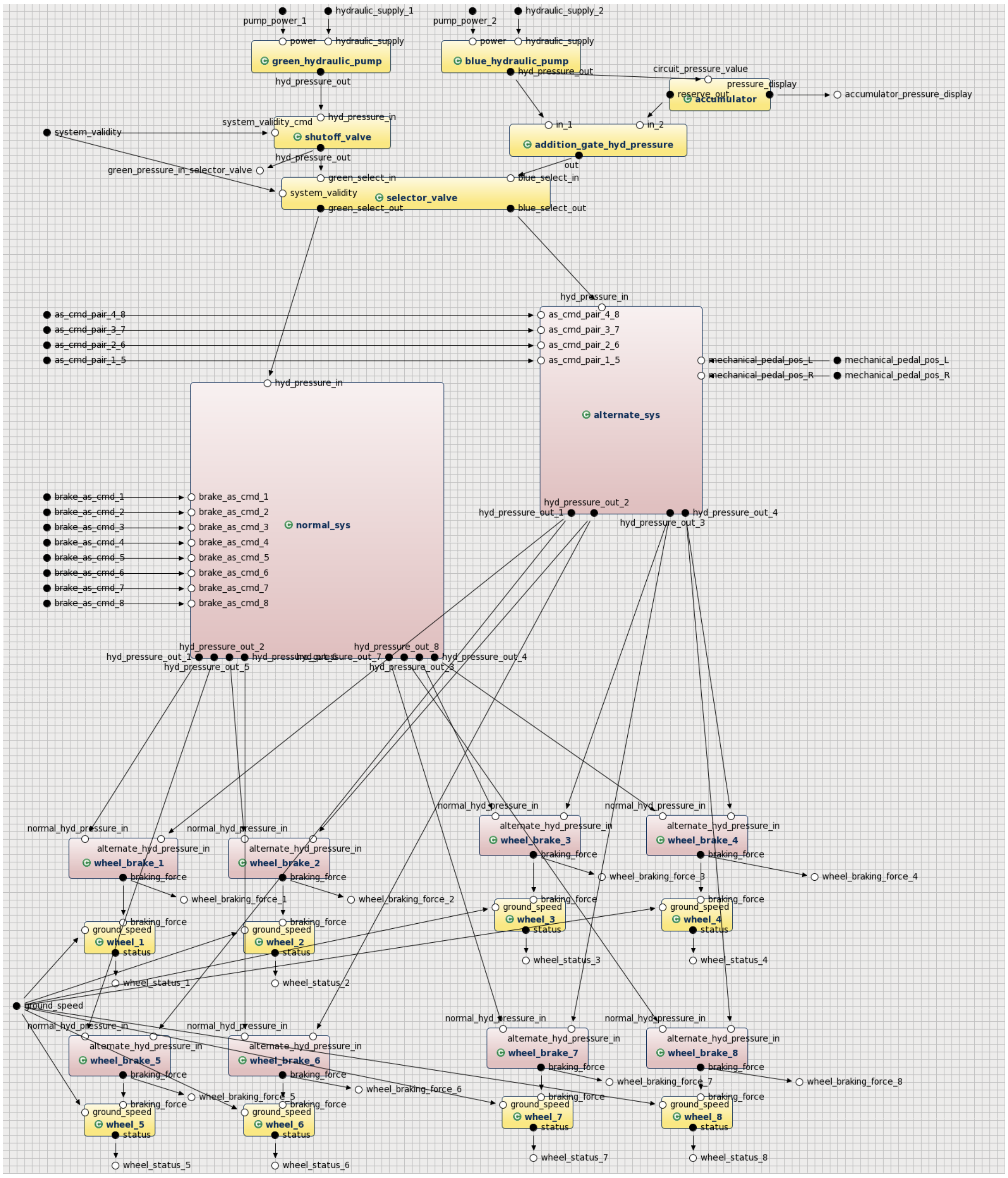


Figure 85: Physical System decomposition

## F.9 Normal Brake System

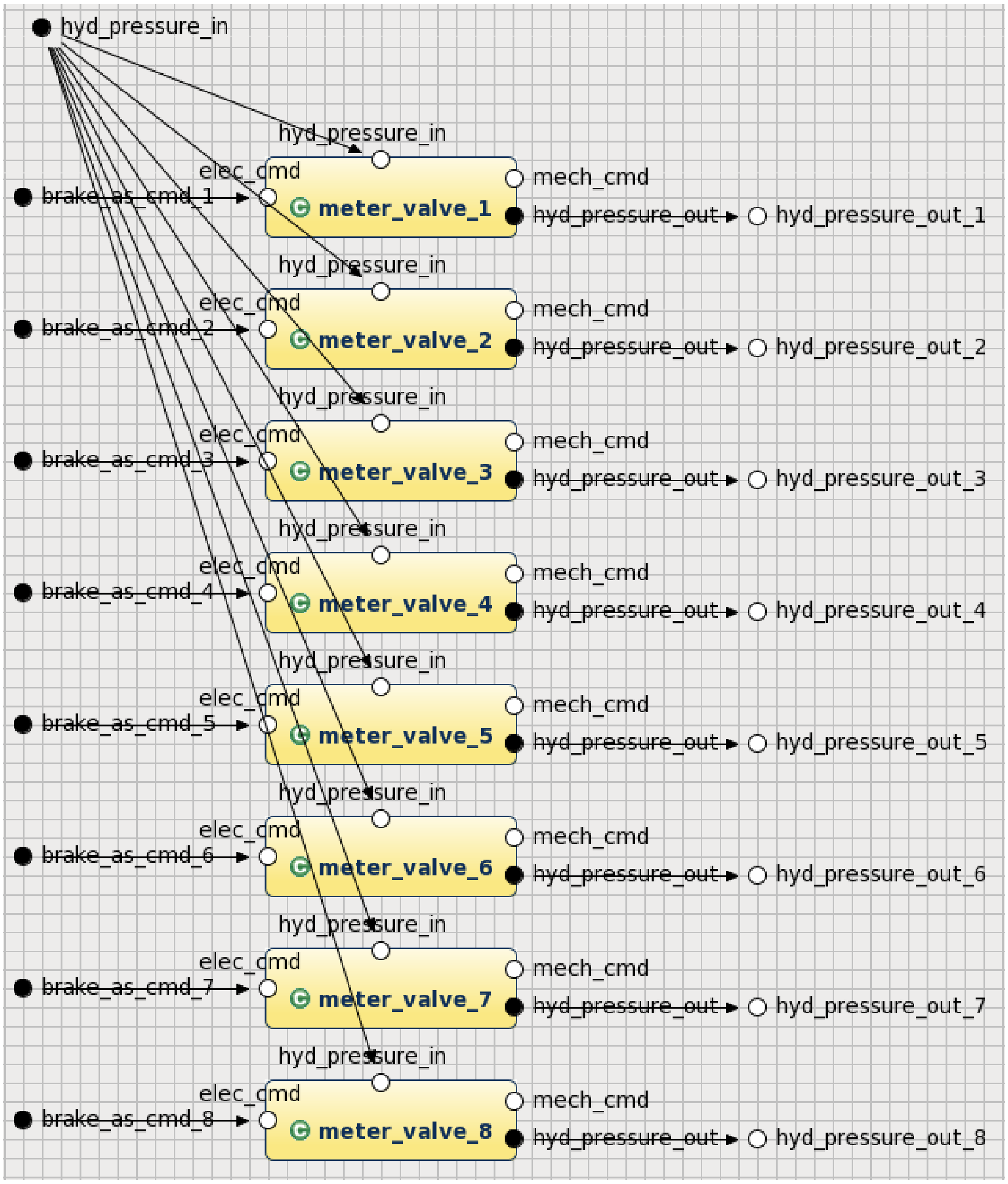


Figure 86: Normal Brake System decomposition

## F.10 Alternate Brake System

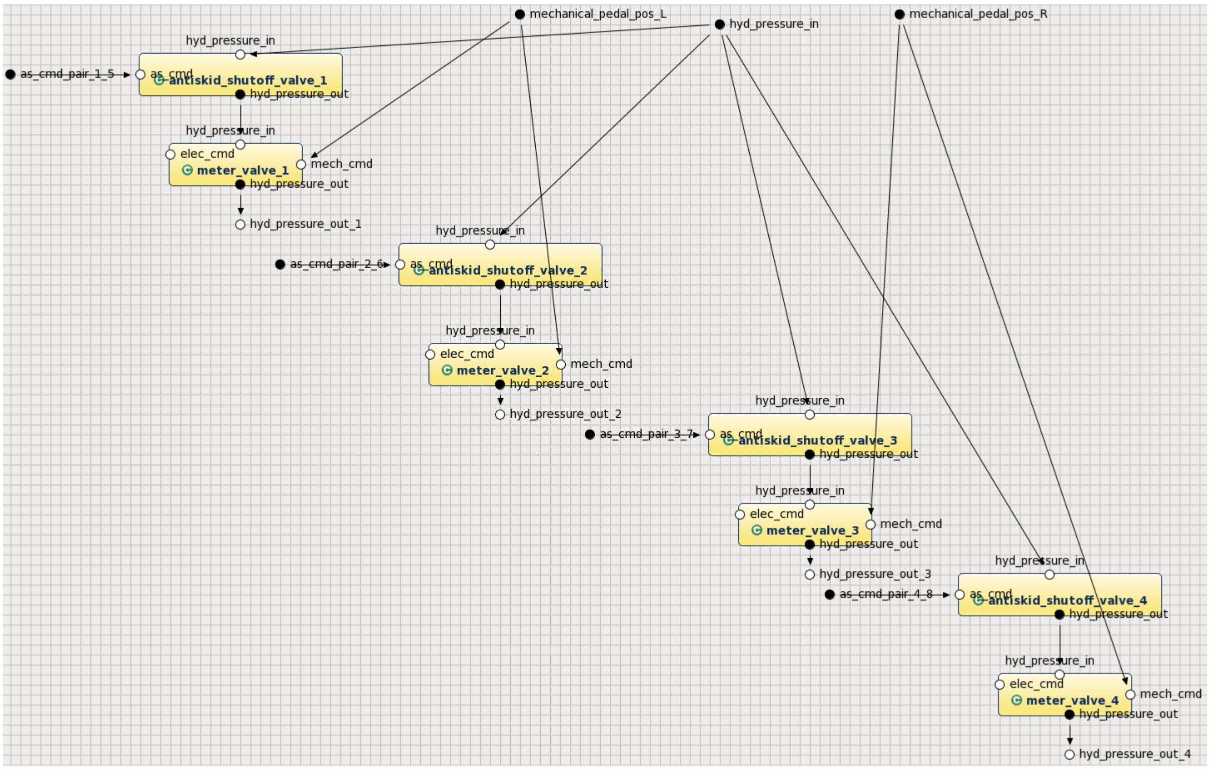


Figure 87: Alternate Brake System decomposition

## F.11 Wheel Brake

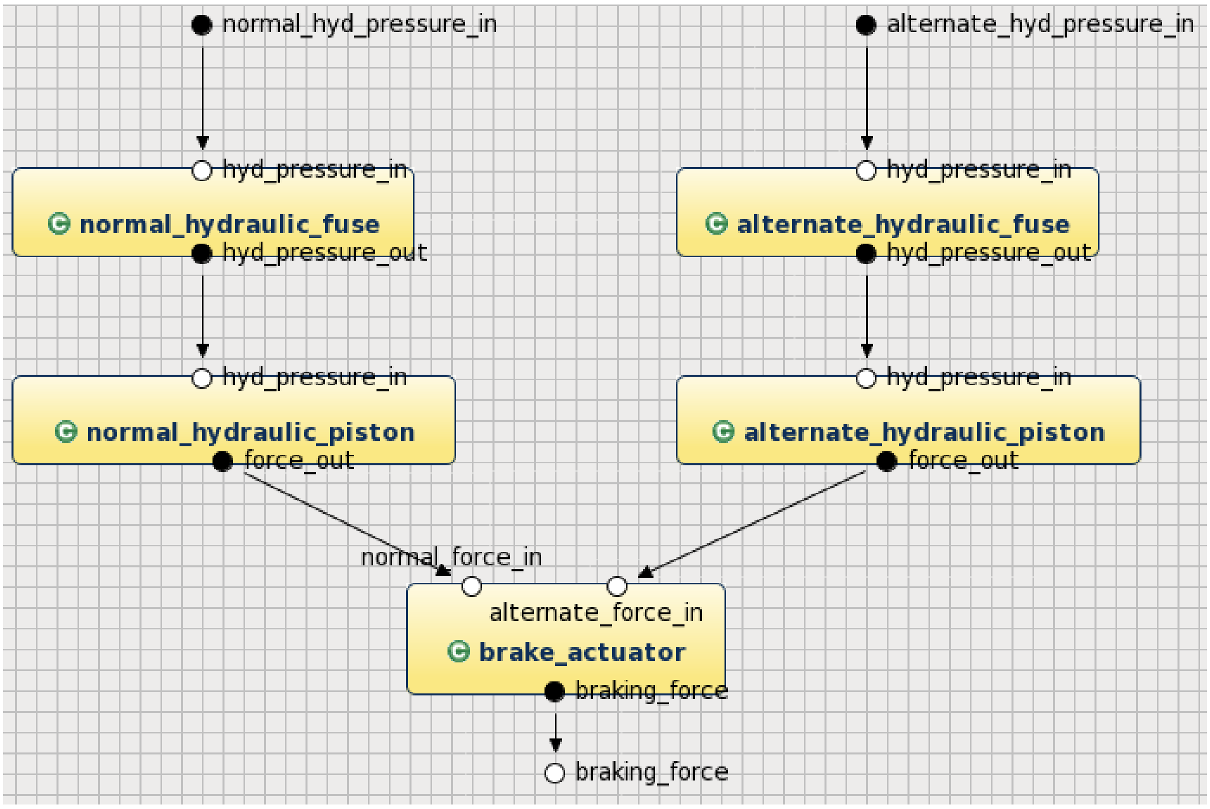


Figure 88: Wheel Brake decomposition

# G Hierarchical Fault Tree example

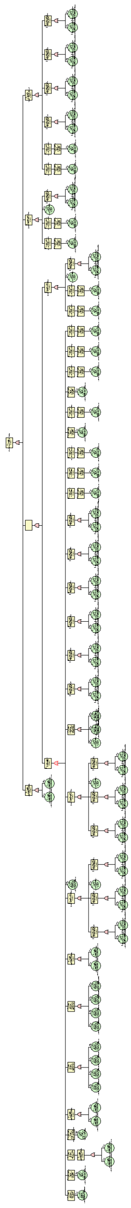


Figure 89: Example of generated Hierarchical Fault Tree

# H WBS Arch1 MBSA results

| Arch/Prop/Faults | | | Prob | $\|mcs\| = 1$ | $\|mcs\| = 2$ | $\|mcs\| = 3$ | $\|mcs\| = 4$ | $\|mcs\| = 5$ | full |
|---|---|---|---|---|---|---|---|---|---|
| arch1 | S18-WBS-R-0321 | full_faults | 1.45e-04 | 17 | 2 | 0 | 0 | 0 | N |
| | | set1 | 1.75e-09 | 0 | 2 | 0 | 0 | 0 | N |
| | | set2 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set3 | 1.45e-04 | 17 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 8.00e-07 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 1.00e-40 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 1.44e-04 | 16 | 0 | 0 | 0 | 0 | N |
| | S18-WBS-R-0322-left | full_faults | 1.45e-04 | 17 | 2 | 0 | 28561 | 0 | Y |
| | | set1 | 1.75e-09 | 0 | 2 | 0 | 1296 | 0 | Y |
| | | set2 | 4.65e-17 | 0 | 0 | 0 | 625 | 0 | Y |
| | | set3 | 1.45e-04 | 17 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 8.00e-07 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 1.00e-20 | 0 | 0 | 0 | 16 | 0 | Y |
| | | set6 | 1.44e-04 | 16 | 0 | 0 | 1296 | 0 | Y |
| | S18-WBS-R-0322-right | full_faults | 1.45e-04 | 17 | 2 | 0 | 28561 | 0 | Y |
| | | set1 | 1.75e-09 | 0 | 2 | 0 | 1296 | 0 | Y |
| | | set2 | 4.65e-17 | 0 | 0 | 0 | 625 | 0 | Y |
| | | set3 | 1.45e-04 | 17 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 8.00e-07 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 1.00e-20 | 0 | 0 | 0 | 16 | 0 | Y |
| | | set6 | 1.44e-04 | 16 | 0 | 0 | 1296 | 0 | Y |
| | S18-WBS-R-0323 | full_faults | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set1 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set2 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set3 | 1.85e-81 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 9.77e-54 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | S18-WBS-R-0324 | full_faults | 2.50e-11 | 0 | 1 | 0 | 0 | 8192 | N |
| | | set1 | 8.17e-41 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set2 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set3 | 4.30e-41 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 2.50e-11 | 0 | 1 | 0 | 0 | 0 | Y |
| | | set6 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | S18-WBS-R-0325-wheel1 | full_faults | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 0 | 0 | 0 | 0 | Y |
| | | set2 | 7.26e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 9.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 1.87e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel2 | full_faults | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 0 | 0 | 0 | 0 | Y |
| | | set2 | 7.26e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 9.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 1.87e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel3 | full_faults | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 0 | 0 | 0 | 0 | Y |
| | | set2 | 7.26e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 9.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 1.87e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel4 | full_faults | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 0 | 0 | 0 | 0 | Y |
| | | set2 | 7.26e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 9.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 1.87e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel5 | full_faults | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 0 | 0 | 0 | 0 | Y |
| | | set2 | 7.26e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 9.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 1.87e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel6 | full_faults | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 0 | 0 | 0 | 0 | Y |
| | | set2 | 7.26e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 9.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 1.87e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel7 | full_faults | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 0 | 0 | 0 | 0 | Y |
| | | set2 | 7.26e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 9.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 1.87e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel8 | full_faults | 9.63e-05 | 9 | 0 | 0 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 0 | 0 | 0 | 0 | Y |
| | | set2 | 7.26e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 9.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |

|  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  | set6 | 1.87e-05 | 4 | 0 | 0 | 0 | 0 | Y |
|  | braking_implies_cmd_w1 | full_faults | 1.11e-04 | 13 | 1 | 0 | 0 | 0 | Y |
|  |  | set1 | 1.95e-05 | 6 | 0 | 0 | 0 | 0 | Y |
|  |  | set2 | 7.26e-05 | 4 | 0 | 0 | 0 | 0 | Y |
|  |  | set3 | 9.00e-06 | 1 | 1 | 0 | 0 | 0 | Y |
|  |  | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
|  |  | set5 | 1.00e-05 | 2 | 0 | 0 | 0 | 0 | Y |
|  |  | set6 | 2.85e-05 | 7 | 0 | 0 | 0 | 0 | Y |
|  | cmd_implies_braking_w1 | full_faults | 2.57e-04 | 30 | 2 | 0 | 0 | 0 | Y |
|  |  | set1 | 1.95e-05 | 6 | 2 | 0 | 0 | 0 | Y |
|  |  | set2 | 8.26e-05 | 5 | 0 | 0 | 0 | 0 | Y |
|  |  | set3 | 1.45e-04 | 17 | 0 | 0 | 0 | 0 | Y |
|  |  | set4 | 8.00e-07 | 1 | 0 | 0 | 0 | 0 | Y |
|  |  | set5 | 1.00e-05 | 2 | 0 | 0 | 0 | 0 | Y |
|  |  | set6 | 1.63e-04 | 22 | 0 | 0 | 0 | 0 | Y |

Table 9: Fault trees results for arch1

# I WBS Arch2 MBSA results

| Arch/Prop/Faults | | | Prob | $\|mcs\| = 1$ | $\|mcs\| = 2$ | $\|mcs\| = 3$ | $\|mcs\| = 4$ | $\|mcs\| = 5$ | full |
|---|---|---|---|---|---|---|---|---|---|
| arch2 | S18-WBS-R-0321 | full_faults | 4.51e-10 | 0 | 6 | 1252 | 629 | - | N |
| | | set1 | 3.50e-10 | 0 | 2 | 2 | 0 | 2592 | Y |
| | | set2 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set3 | 5.25e-27 | 0 | 0 | 0 | 0 | 1 | Y |
| | | set4 | 1.83e-32 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 1.00e-10 | 0 | 4 | 0 | 0 | 64 | Y |
| | | set6 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | S18-WBS-R-0322-left | full_faults | 1.00e-05 | 2 | 2 | 732 | 47583 | - | N |
| | | set1 | 3.50e-10 | 0 | 2 | 74 | 81 | 0 | Y |
| | | set2 | 4.65e-17 | 0 | 0 | 0 | 625 | 0 | Y |
| | | set3 | 6.48e-17 | 0 | 0 | 1 | 33 | 216 | Y |
| | | set4 | 1.08e-22 | 0 | 0 | 0 | 2 | 0 | Y |
| | | set5 | 1.00e-05 | 2 | 0 | 0 | 16 | 0 | Y |
| | | set6 | 1.77e-17 | 0 | 0 | 0 | 20817 | 0 | Y |
| | S18-WBS-R-0322-right | full_faults | 1.00e-05 | 2 | 2 | 732 | 47583 | - | N |
| | | set1 | 3.50e-10 | 0 | 2 | 74 | 81 | 0 | Y |
| | | set2 | 4.65e-17 | 0 | 0 | 0 | 625 | 0 | Y |
| | | set3 | 6.48e-17 | 0 | 0 | 1 | 33 | 216 | Y |
| | | set4 | 1.08e-22 | 0 | 0 | 0 | 2 | 0 | Y |
| | | set5 | 1.00e-05 | 2 | 0 | 0 | 16 | 0 | Y |
| | | set6 | 1.77e-17 | 0 | 0 | 0 | 20817 | 0 | Y |
| | S18-WBS-R-0323 | full_faults | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set1 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set2 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set3 | 3.44e-47 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 9.77e-54 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 1.05e-28 | 0 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0324 | full_faults | 2.50e-11 | 0 | 1 | 0 | 38 | 10859 | N |
| | | set1 | 1.04e-24 | 0 | 0 | 0 | 0 | 324 | Y |
| | | set2 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set3 | 5.25e-27 | 0 | 0 | 0 | 0 | 1 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 2.50e-11 | 0 | 1 | 0 | 0 | 0 | Y |
| | | set6 | 4.22e-28 | 0 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel1 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel2 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel3 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel4 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel5 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel6 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel7 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel8 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | braking_implies_cmd_w1 | full_faults | 1.25e-04 | 10 | 40 | 2651 | 7395 | 9636 | Y |
| | | set1 | 9.75e-06 | 3 | 24 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 2.16e-11 | 0 | 3 | 75 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 1.00e-05 | 2 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | cmd_implies_braking_w1 | full_faults | 1.13e-04 | 13 | 30 | 8053 | 3815 | 2873 | Y |
| | | set1 | 9.75e-06 | 3 | 14 | 2 | 0 | 0 | Y |
| | | set2 | 8.26e-05 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 2.16e-11 | 0 | 3 | 75 | 0 | 0 | Y |
| | | set4 | 6.50e-07 | 1 | 0 | 2 | 0 | 0 | Y |
| | | set5 | 2.00e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 3456 | 0 | 0 | Y |

Table 10: Fault trees results for arch2

# J WBS Arch2bis MBSA results

| Arch/Prop/Faults | | | Prob | $\|mcs\| = 1$ | $\|mcs\| = 2$ | $\|mcs\| = 3$ | $\|mcs\| = 4$ | $\|mcs\| = 5$ | full |
|---|---|---|---|---|---|---|---|---|---|
| arch2bis | S18-WBS-R-0321 | full_faults | 4.51e-10 | 0 | 6 | 627 | 629 | - | N |
| | | set1 | 3.50e-10 | 0 | 2 | 2 | 0 | 2592 | Y |
| | | set2 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set3 | 5.25e-27 | 0 | 0 | 0 | 0 | 1 | Y |
| | | set4 | 1.83e-32 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 1.00e-10 | 0 | 4 | 0 | 0 | 64 | Y |
| | | set6 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | S18-WBS-R-0322-left | full_faults | 1.00e-05 | 2 | 2 | 203 | 46287 | - | N |
| | | set1 | 3.50e-10 | 0 | 2 | 74 | 81 | 0 | Y |
| | | set2 | 4.65e-17 | 0 | 0 | 0 | 625 | 0 | Y |
| | | set3 | 6.48e-17 | 0 | 0 | 1 | 33 | 216 | Y |
| | | set4 | 1.08e-22 | 0 | 0 | 0 | 2 | 0 | Y |
| | | set5 | 1.00e-05 | 2 | 0 | 0 | 16 | 0 | Y |
| | | set6 | 1.77e-17 | 0 | 0 | 0 | 20817 | 0 | Y |
| | S18-WBS-R-0322-right | full_faults | 1.00e-05 | 2 | 2 | 203 | 46287 | - | N |
| | | set1 | 3.50e-10 | 0 | 2 | 74 | 81 | 0 | Y |
| | | set2 | 4.65e-17 | 0 | 0 | 0 | 625 | 0 | Y |
| | | set3 | 6.48e-17 | 0 | 0 | 1 | 33 | 216 | Y |
| | | set4 | 1.08e-22 | 0 | 0 | 0 | 2 | 0 | Y |
| | | set5 | 1.00e-05 | 2 | 0 | 0 | 16 | 0 | Y |
| | | set6 | 1.77e-17 | 0 | 0 | 0 | 20817 | 0 | Y |
| | S18-WBS-R-0323 | full_faults | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set1 | 8.17e-41 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set2 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set3 | 3.44e-47 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 9.77e-54 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 1.05e-28 | 0 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0324 | full_faults | 2.50e-11 | 0 | 1 | 0 | 2 | 8729 | N |
| | | set1 | 3.16e-25 | 0 | 0 | 0 | 0 | 162 | Y |
| | | set2 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set3 | 5.25e-27 | 0 | 0 | 0 | 0 | 1 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 2.50e-11 | 0 | 1 | 0 | 0 | 0 | Y |
| | | set6 | 4.22e-28 | 0 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel1 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel2 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel3 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel4 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel5 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel6 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel7 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel8 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | braking_implies_cmd_w1 | full_faults | 1.25e-04 | 10 | 24 | 2647 | 4530 | 59 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 2.16e-11 | 0 | 3 | 75 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 1.00e-05 | 2 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | cmd_implies_braking_w1 | full_faults | 1.13e-04 | 13 | 30 | 7428 | 3815 | 1768 | Y |
| | | set1 | 9.75e-06 | 3 | 14 | 2 | 0 | 0 | Y |
| | | set2 | 8.26e-05 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 2.16e-11 | 0 | 3 | 75 | 0 | 0 | Y |
| | | set4 | 6.50e-07 | 1 | 0 | 2 | 0 | 0 | Y |
| | | set5 | 2.00e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 3456 | 0 | 0 | Y |

Table 11: Fault trees results for arch2bis

# K WBS Arch3 MBSA results

| Arch/Prop/Faults | | | Prob | $\|mcs\| = 1$ | $\|mcs\| = 2$ | $\|mcs\| = 3$ | $\|mcs\| = 4$ | $\|mcs\| = 5$ | full |
|---|---|---|---|---|---|---|---|---|---|
| arch3 | S18-WBS-R-0321 | full_faults | 4.51e-10 | 0 | 6 | 1252 | 629 | - | N |
| | | set1 | 3.50e-10 | 0 | 2 | 2 | 0 | 2592 | Y |
| | | set2 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set3 | 5.25e-27 | 0 | 0 | 0 | 0 | 1 | Y |
| | | set4 | 1.83e-32 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 1.00e-10 | 0 | 4 | 0 | 0 | 64 | Y |
| | | set6 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | S18-WBS-R-0322-left | full_faults | 1.00e-05 | 2 | 2 | 732 | 47583 | - | N |
| | | set1 | 3.50e-10 | 0 | 2 | 74 | 81 | 0 | Y |
| | | set2 | 4.65e-17 | 0 | 0 | 0 | 625 | 0 | Y |
| | | set3 | 6.48e-17 | 0 | 0 | 1 | 33 | 216 | Y |
| | | set4 | 1.08e-22 | 0 | 0 | 0 | 2 | 0 | Y |
| | | set5 | 1.00e-05 | 2 | 0 | 0 | 16 | 0 | Y |
| | | set6 | 1.77e-17 | 0 | 0 | 0 | 20817 | 0 | Y |
| | S18-WBS-R-0322-right | full_faults | 1.00e-05 | 2 | 2 | 732 | 47583 | - | N |
| | | set1 | 3.50e-10 | 0 | 2 | 74 | 81 | 0 | Y |
| | | set2 | 4.65e-17 | 0 | 0 | 0 | 625 | 0 | Y |
| | | set3 | 6.48e-17 | 0 | 0 | 1 | 33 | 216 | Y |
| | | set4 | 1.08e-22 | 0 | 0 | 0 | 2 | 0 | Y |
| | | set5 | 1.00e-05 | 2 | 0 | 0 | 16 | 0 | Y |
| | | set6 | 1.77e-17 | 0 | 0 | 0 | 20817 | 0 | Y |
| | S18-WBS-R-0323 | full_faults | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set1 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set2 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set3 | 3.44e-47 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 9.77e-54 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 1.05e-28 | 0 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0324 | full_faults | 2.50e-11 | 0 | 1 | 0 | 38 | 10859 | N |
| | | set1 | 1.04e-24 | 0 | 0 | 0 | 0 | 324 | Y |
| | | set2 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set3 | 5.25e-27 | 0 | 0 | 0 | 0 | 1 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 2.50e-11 | 0 | 1 | 0 | 0 | 0 | Y |
| | | set6 | 4.22e-28 | 0 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel1 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel2 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel3 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel4 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel5 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel6 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel7 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel8 | full_faults | 1.20e-04 | 9 | 19 | 2597 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | braking_implies_cmd_w1 | full_faults | 1.25e-04 | 10 | 40 | 2651 | 7395 | 9636 | Y |
| | | set1 | 9.75e-06 | 3 | 24 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 2.16e-11 | 0 | 3 | 75 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 1.00e-05 | 2 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | cmd_implies_braking_w1 | full_faults | 1.13e-04 | 13 | 30 | 8053 | 3815 | 2873 | Y |
| | | set1 | 9.75e-06 | 3 | 14 | 2 | 0 | 0 | Y |
| | | set2 | 8.26e-05 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 2.16e-11 | 0 | 3 | 75 | 0 | 0 | Y |
| | | set4 | 6.50e-07 | 1 | 0 | 2 | 0 | 0 | Y |
| | | set5 | 2.00e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 3456 | 0 | 0 | Y |

Table 12: Fault trees results for arch3

# L WBS Arch4 MBSA results

| Arch/Prop/Faults | | | Prob | $\|mcs\| = 1$ | $\|mcs\| = 2$ | $\|mcs\| = 3$ | $\|mcs\| = 4$ | $\|mcs\| = 5$ | full |
|---|---|---|---|---|---|---|---|---|---|
| arch4 | S18-WBS-R-0321 | full_faults | 4.51e-10 | 0 | 6 | 627 | 629 | - | N |
| | | set1 | 3.50e-10 | 0 | 2 | 2 | 0 | 2592 | Y |
| | | set2 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set3 | 5.25e-27 | 0 | 0 | 0 | 0 | 1 | Y |
| | | set4 | 1.83e-32 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 1.00e-10 | 0 | 4 | 0 | 0 | 64 | Y |
| | | set6 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | S18-WBS-R-0322-left | full_faults | 1.00e-05 | 2 | 2 | 203 | 46287 | - | N |
| | | set1 | 3.50e-10 | 0 | 2 | 74 | 81 | 0 | Y |
| | | set2 | 4.65e-17 | 0 | 0 | 0 | 625 | 0 | Y |
| | | set3 | 6.48e-17 | 0 | 0 | 1 | 33 | 216 | Y |
| | | set4 | 1.08e-22 | 0 | 0 | 0 | 2 | 0 | Y |
| | | set5 | 1.00e-05 | 2 | 0 | 0 | 16 | 0 | Y |
| | | set6 | 1.77e-17 | 0 | 0 | 0 | 20817 | 0 | Y |
| | S18-WBS-R-0322-right | full_faults | 1.00e-05 | 2 | 2 | 203 | 46287 | - | N |
| | | set1 | 3.50e-10 | 0 | 2 | 74 | 81 | 0 | Y |
| | | set2 | 4.65e-17 | 0 | 0 | 0 | 625 | 0 | Y |
| | | set3 | 6.48e-17 | 0 | 0 | 1 | 33 | 216 | Y |
| | | set4 | 1.08e-22 | 0 | 0 | 0 | 2 | 0 | Y |
| | | set5 | 1.00e-05 | 2 | 0 | 0 | 16 | 0 | Y |
| | | set6 | 1.77e-17 | 0 | 0 | 0 | 20817 | 0 | Y |
| | S18-WBS-R-0323 | full_faults | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set1 | 8.17e-41 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set2 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set3 | 3.44e-47 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 9.77e-54 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 1.05e-28 | 0 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0324 | full_faults | 2.50e-11 | 0 | 1 | 0 | 2 | 8729 | N |
| | | set1 | 3.16e-25 | 0 | 0 | 0 | 0 | 162 | Y |
| | | set2 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | N |
| | | set3 | 5.25e-27 | 0 | 0 | 0 | 0 | 1 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 2.50e-11 | 0 | 1 | 0 | 0 | 0 | Y |
| | | set6 | 4.22e-28 | 0 | 0 | 0 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel1 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel2 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel3 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel4 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel5 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel6 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel7 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | S18-WBS-R-0325-wheel8 | full_faults | 1.20e-04 | 9 | 12 | 2596 | 0 | 0 | Y |
| | | set1 | 9.75e-06 | 3 | 6 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 1.44e-11 | 0 | 2 | 50 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 5.00e-06 | 1 | 0 | 0 | 0 | 0 | Y |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | braking_implies_cmd_w1 | full_faults | 1.25e-04 | 10 | 24 | 2647 | 4530 | 59 | Y |
| | | set1 | 9.75e-06 | 3 | 12 | 0 | 0 | 0 | Y |
| | | set2 | 1.06e-04 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 2.16e-11 | 0 | 3 | 75 | 0 | 0 | Y |
| | | set4 | 0.00e+00 | 0 | 0 | 0 | 0 | 0 | Y |
| | | set5 | 1.00e-05 | 2 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 1728 | 0 | 0 | Y |
| | cmd_implies_braking_w1 | full_faults | 1.13e-04 | 13 | 30 | 7428 | 3815 | 1768 | Y |
| | | set1 | 9.75e-06 | 3 | 14 | 2 | 0 | 0 | Y |
| | | set2 | 8.26e-05 | 5 | 0 | 0 | 0 | 0 | Y |
| | | set3 | 2.16e-11 | 0 | 3 | 75 | 0 | 0 | Y |
| | | set4 | 6.50e-07 | 1 | 0 | 2 | 0 | 0 | Y |
| | | set5 | 2.00e-05 | 4 | 0 | 0 | 0 | 0 | Y |
| | | set6 | 9.75e-06 | 3 | 0 | 3456 | 0 | 0 | Y |

Table 13: Fault trees results for arch4

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