

A FRAMEWORK FOR AUTOMATED SYSTEM COMPONENT PLACEMENT IN AIRCRAFT CONCEPTUAL DESIGN

Joey Vézina[1] & Susan Liscouët-Hanke[1]

[1]Department of Mechanical, Industrial, and Aerospace Engineering, Concordia University, 1455 De Maisonneuve Blvd. W. Montreal, H3G 1M8

Abstract

Aircraft systems integration is becoming an increasingly important consideration during conceptual design for assessing the feasibility of novel aircraft configurations. Existing knowledge-based approaches do not enable systematic design space exploration and are not suited to unconventional aircraft configurations or novel propulsion system architectures. To address this limitation, this paper introduces the Aircraft Component Installation Optimization (ACI-OPT) framework for automated system component placement during conceptual design. Information available from upstream conceptual design activities is used to define the aircraft, equipment bays, and components in a parametrized structured data format that acts as a single source of truth for the component placement analysis process. Existing systems integration analysis modules are combined into a unified environment to evaluate a component layout according to its main system integration aspects, namely thermal management, maintainability, safety, and wire routing. The modules output system integration risk scores and risk zone containment information, providing layout-dependent metrics to evaluate component placement. In the current implementation, the thermal risk assessment, maintenance risk assessment, and conceptual-level particular risk analysis are used to identify discipline-specific integration issues and guide targeted design space exploration procedures to propose improved component layouts. The methodology is demonstrated on an avionics rack, an underfloor equipment bay, and an aft equipment bay of a notional conventional business jet aircraft. The results show that the proposed approach enables the evaluation of component layouts with respect to their primary integration constraints and supports the systematic development of improved configurations beyond current knowledge-based component placement methods.

Keywords: aircraft conceptual design, aircraft systems, systems integration, component placement, multidisciplinary analysis

1 Introduction

Global decarbonization efforts prompted by international climate commitments [1] are driving the development of novel aircraft configurations and technologies in the aerospace industry. Research efforts focus on unconventional aircraft configurations to improve aerodynamic efficiency and reduce fuel consumption, such as the Flying-V [2], blended-wing body [3], and truss-braced wing [4]. In parallel, complementary efforts target alternative propulsion systems, including hybrid-electric [5], fully electric [6], and hydrogen-based technologies [7].

These unconventional aircraft configurations and novel propulsion technologies introduce significant system integration challenges [6, 8–11]. Traditional system integration practices rely on established design rules and experience gained from multiple aircraft programs, requiring extensive manual iterations among experts across various disciplines [12, 13]. This approach is generally effective when the aircraft configuration, available systems installation volume, and physical component types are

similar to those of existing aircraft. However, these methods are less suitable for novel aircraft configurations, where internal geometries differ significantly from those of tube-and-wing aircraft [14]. Similarly, emerging propulsion system technologies introduce new components and integration requirements related to thermal management, maintainability, safety, and interconnection systems that may not be captured by existing design rules [15, 16]. As a result, design precedent alone is insufficient to assess the feasibility of proposed aircraft configurations and system architectures during conceptual design.

The conceptual design process must therefore evolve to support the development of next-generation aircraft. Systematic methods for assessing system integration feasibility can be introduced during the conceptual design phase, as the required information is already available from upstream design activities. Figure 1 shows where the component placement analysis fits into the existing conceptual design process and how it relates to existing design activities. The conceptual design process typically begins with overall aircraft design (OAD), where aircraft-level requirements are translated into an initial aircraft configuration and top-level aircraft parameters are determined, enabling the initial allocation of systems installation volumes. In parallel, the system architecture definition translates the aircraft's functional needs into logical and physical components, identifying the components to be integrated, their functional dependencies, and their physical connections. Preliminary sizing of aircraft systems provides component-level characteristics relevant to systems integration, such as size, weight, power consumption, heat dissipation, and reliability. These parameters form the basis for formulating the component placement problem in conceptual design, where physical system components must be integrated within available installation volumes while satisfying multidisciplinary integration constraints.

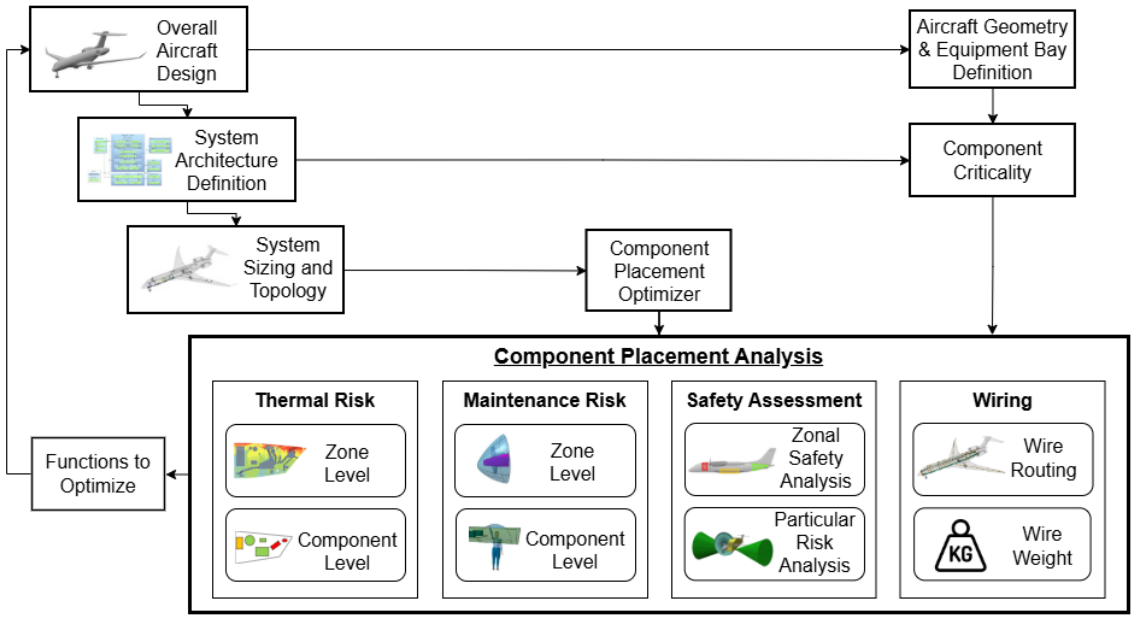


Figure 1 – Component placement analysis framework within the conceptual design process.

Introducing component placement in early design stages allows the integration feasibility of candidate aircraft configurations and novel system architectures to be assessed before key design decisions are fixed. Rather than addressing integration issues through repeated discipline-specific iterations later in the design process, component layouts can be systematically evaluated against the primary constraints that drive systems integration. This allows aircraft- and system-level modifications to be identified earlier in the design process, including changes to the allocated installation volume, cooling capacity, component selection, or component placement. Early identification of these issues reduces the risk of major integration problems in later design phases, which may lead to costly redesigns. In addition, the systematic evaluation of component layouts enables the broader exploration of the systems integration design space and supports the identification of improved design solutions.

Novel design tools are required to address the system integration challenges of next-generation sustainable aircraft. Previous work in the Aircraft Systems Lab at Concordia University focused on developing conceptual-level aircraft system analysis tools to evaluate component layouts within equipment bays with respect to their primary system integration constraints, specifically their thermal properties [17–20], maintainability [21, 22], safety [23, 24], and electrical wiring interconnection system (EWIS) aspects [25]. This paper builds on previous work to introduce the Aircraft Component Installation Optimization (ACI-OPT) framework, a comprehensive framework that integrates individual disciplinary analyses to enable automated placement and evaluation of aircraft system components during the conceptual design phase. The framework allows designers to conduct rapid engineering assessments of many design solutions without requiring manual iterations or time-consuming high-fidelity analyses. Automated design space exploration methods are implemented to improve the system integration aspects of proposed component layouts based on thermal and maintenance considerations, while also accounting for threat envelopes from the particular risk analysis. This establishes the foundation for the future integration of zonal safety and EWIS aspects, as well as the implementation of formal optimization methods.

Section 2 introduces relevant system integration practices in business jet aircraft to contextualize the application of the methodology in this work. Section 3 provides a review of the literature regarding aircraft system component placement, and explores how similar problems were addressed in adjacent fields. Section 4 presents the ACI-OPT methodology for evaluating component layouts during conceptual design and developing improved solutions. The methodology is applied to notional equipment bays of a typical business jet aircraft in Section 5. Section 6 concludes the paper by summarizing the key findings and identifying directions for future work.

2 System Integration Background for Business Jet Aircraft

The ACI-OPT framework is intended to be applicable to aircraft system component placement problems during conceptual design for both conventional and unconventional aircraft configurations. Although the development of the framework is motivated by the integration challenges of next-generation aircraft, it is first demonstrated on a conventional business jet as a practical application case. Business aircraft are well-suited for this initial application because their limited installation volume, especially in the underfloor section, makes component placement particularly challenging. The notional business jet configuration and its equipment bays considered in this work are shown in Figure 2. While configurations may vary, the business jet considered in this paper contains two forward avionics racks (FAR), an underfloor equipment bay (UEB), and an aft equipment bay (AEB). Each equipment bay provides a distinct installation environment and introduces its own specific integration considerations.

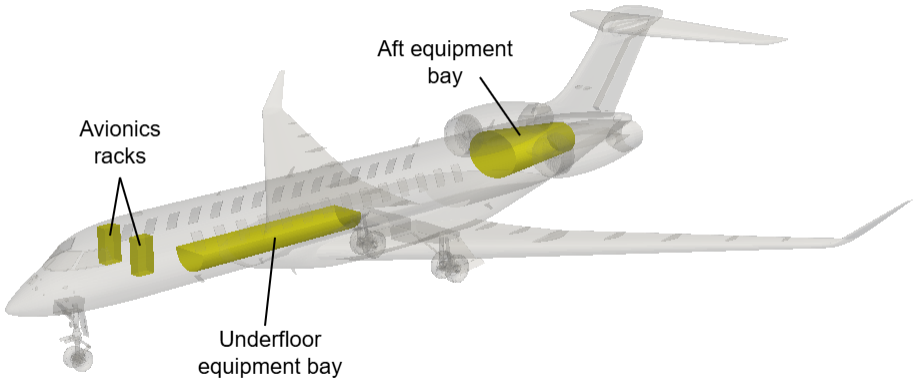


Figure 2 – Notional business jet configuration adapted from [26] with equipment bays.

FARs are typically located between the cockpit and the passenger cabin. They provide a structured installation environment, with line-replaceable units (LRUs) arranged on shelves. The cooling flow enters from the bottom of the rack and exits through an outlet above the rack. Avionics racks are generally favorable for maintenance because they can be accessed directly from the front and serviced while standing. The components are relatively light and have simple mechanical and electrical connections, further reducing the maintenance effort. The LRUs are also of a similar type, limiting the critical interactions between different systems that introduce zonal safety issues. As a result, thermal management is the primary driver of component placement in the avionics rack, with the main considerations being the position of thermally sensitive components relative to the cooling flow and the distribution of heat dissipation throughout the rack. Although FARs provide a suitable environment for system installation and maintenance access, they occupy valuable cabin volume, which motivates designers to limit the space allocated to them.

The UEB is located below the passenger cabin, forward of the center wing box, and mainly contains avionics and electrical units due to its limited height in business aircraft. These components are arranged in rows, on either side of a central aisle, which acts as a crawl space for maintenance access. As for the FARs, the UEB contains components of similar type, making it less critical from a zonal safety perspective. However, thermal management and maintainability can both be challenging. Components located farther along the cooling flow path may be subject to less favorable thermal conditions because the air temperature increases as heat is absorbed from upstream components. From a maintenance perspective, components located farther from the access panel are more difficult to service. Although the thermal behavior of the components can be influenced by their positions, it is primarily governed by the bay's ventilation characteristics. As such, the proposed approach to improve the component layout in the UEB consists of arranging the components to favor maintainability, while varying the ventilation parameters to obtain a thermally feasible configuration. In addition, designers generally aim to maximize the number of components in the UEB to reduce the number of components required in the above-floor FARs.

The AEB is an unpressurized zone located aft of the passenger cabin and contains components from several aircraft systems, including the hydraulic, environmental control, avionics, and instrumentation systems. Unlike the FARs and UEB, the components are distributed throughout the available installation volume, rather than arranged in shelves or rows. This creates a more strongly coupled component placement problem across the different integration disciplines. Thermal behavior depends on several factors, including the position of the components relative to the cooling flow path and the local heat dissipation distribution. Maintainability depends on the maintenance characteristics of each component and their accessibility within the equipment bay. Safety considerations are also more significant than in the other equipment bays because the AEB contains components from several different systems, introducing critical interactions between components and between components and the bay environment. For aft-mounted engine configurations, engine rotor burst zones generally intersect the AEB, making the segregation of redundant components an important placement consideration. Consequently, the AEB is less suited to simple rule-based layout modifications and generally requires a broader evaluation of different component layouts. Typically, aircraft designers aim to minimize the size of the AEB to reduce the aircraft wetted area and weight.

3 Literature Review

The component placement problem has been addressed across a wide range of engineering applications. In aircraft, system components are typically positioned using knowledge-based approaches. These methods have been applied to both commercial aircraft configurations [11, 12], and business jet aircraft [13], where knowledge acquired through design precedent and component-specific installation rules are used to generate initial component layouts. Other studies have aimed to move beyond knowledge-based approaches by accounting for system integration constraints. Şahin and Oliva [27] proposed a methodology for aircraft system component placement while considering multiple integration aspects, but the approach lacks an automated implementation. Fioriti et al. [28] investigated component placement within an aircraft design optimization environment, but failed to identify feasi-

ble solutions. Xue et al. [29] considered the placement of components in an electronic equipment cabin, but the analysis was limited to maintenance and geometric aspects.

Component placement and layout optimization have also been addressed in other aerospace applications. For spacecraft, Luo et al. [30] improved maintainability aspects using particle swarm optimization, and Cuco et al. [31] focused on thermal and geometric constraints through multi-objective optimization. Similar approaches have been investigated for unmanned aerial vehicles, where Torrigiani et al. [32] considered thermal aspects in a multidisciplinary design optimization framework, and Ng and Leng [33] applied a genetic algorithm (GA) to optimize a quadrotor layout under geometric and center of gravity constraints. In the automotive industry, Lee et al. [34] applied a robot motion planning approach to optimize cooling system layouts, while Miao et al. [35] optimized the layout of a military truck using a GA.

The literature review shows that key challenges remain in the automated placement of aircraft system components, particularly regarding the handling of multiple competing constraints in early design stages. This work addresses these gaps by integrating multiple system integration analyses in the component placement process to evaluate and improve equipment bay layouts.

4 Methodology

The proposed methodology defines a framework for the automated placement and multidisciplinary evaluation of aircraft system components during conceptual design. Although the component placement problem is closely linked to upstream conceptual design activities, the present work does not focus on the complete process chain from requirements capture and OAD to component placement. Rather, the focus is on developing the component placement framework with the required inputs assumed to be known from the upstream conceptual design activities. Future work will address the integration of component placement considerations in more comprehensive aircraft design workflows.

The methodology first presents an overview of the component placement process and introduces the standardized aircraft parametrization, which provides the input data for the ACI-OPT framework. The disciplinary analysis modules used to evaluate equipment bay configurations are then summarized, followed by a description of the design space exploration methods developed to generate improved component layouts. Finally, the implementation aspects of the framework are discussed.

4.1 Overview of the Component Placement Analysis Process

The component placement process, shown in Figure 3, links the standardized aircraft parametrization of Section 4.2, the system integration analysis modules described in Section 4.3, and the design space exploration procedures discussed in Section 4.4. The process begins with aircraft-, system-, and component-level information assumed to be known from upstream conceptual design activities. This information defines the aircraft configuration, available equipment bay volumes, component properties, and system interconnections required to formulate the component placement problem.

The inputs from upstream conceptual design activities, such as OAD, system architecture, and system sizing, enable the aircraft, equipment bays, and components to be defined parametrically and consolidated into a standardized data format. This common data format is used for all system integration analyses, ensuring that all disciplines are evaluated using a consistent configuration definition.

The proposed component layouts are evaluated using discipline-specific analysis modules to provide rapid, low-fidelity assessments of their main system integration aspects. The thermal risk assessment outputs risk scores that characterize the thermal behavior of the equipment bay and its components. The maintenance risk assessment also uses a score-based approach to evaluate the maintainability of the proposed component layout. The safety assessment uses zonal safety scores to represent zonal safety risks and specifies which components are located within particular risk threat envelopes. The automated wire routing evaluates routing feasibility and estimates the wire length and weight of a given configuration. The results of the system integration analyses make it possible to identify the specific issues associated with a given configuration.

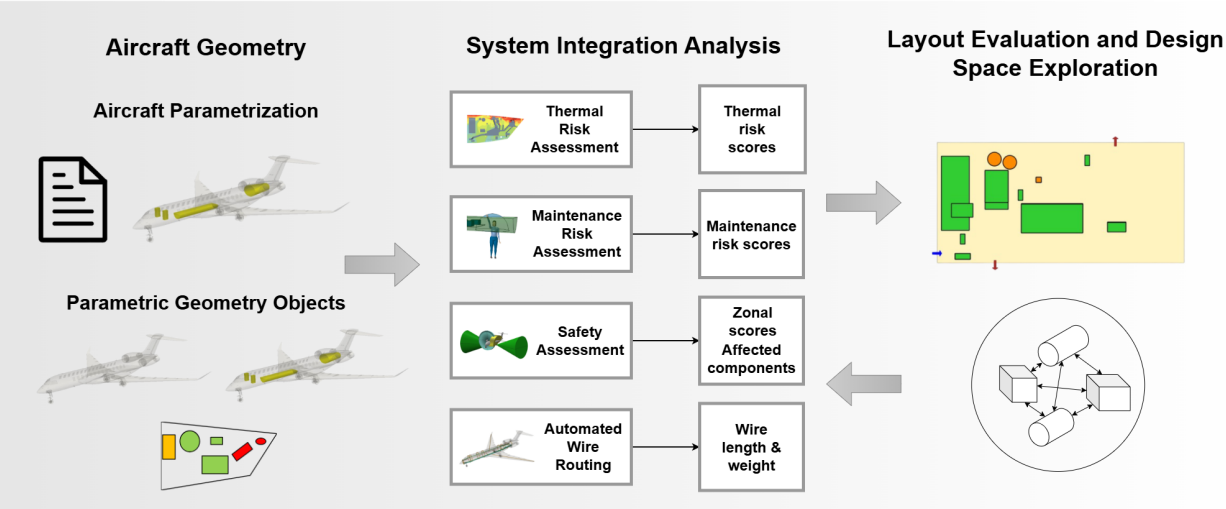


Figure 3 – Component placement analysis process.

At this stage of the framework development, the design space exploration methods presented in Section 4.4 use the thermal risk assessment, maintenance risk assessment, and conceptual-level particular risk analysis to propose targeted design solutions that improve the component layouts. The term *design space exploration* (DSE) is used because formal optimization methods have not yet been implemented in the ACI-OPT framework. As seen in [28], the high dimensionality and multimodality of the problem, combined with the absence of gradient information, make it difficult for state-of-the-art optimizers to find feasible solutions for configurations with a large number of components, such as the ones presented in this paper. Ongoing work involves incorporating optimization methods into the framework to enable a broader exploration of the design space, thereby supporting the identification of optimal design solutions.

4.2 Standardized Aircraft Parametrization

The ACI-OPT framework relies on a standardized aircraft parametrization to ensure that all analysis modules are executed from a common data source that acts as a single source of truth. This step is necessary to ensure that all analyses are performed from the same configuration definition, avoiding inconsistencies that could arise by defining the configuration separately for each analysis module. The parametrization translates information from upstream conceptual design activities into a structured input format that can be read and processed within the framework, organized into three levels: aircraft level, equipment bay level, and component level. Information from OAD activities is parametrized at the aircraft level, equipment bay definition data is parametrized at the equipment bay level, and information from the physical architecture and system sizing is parametrized at the component level. These levels describe the overall aircraft configuration, the geometry and integration-related characteristics of the equipment bays, and the physical properties of the components, respectively. This hierarchical structure allows the information required for component placement analysis to be stored in a clear, structured manner, enabling candidate layouts to be generated, modified, and evaluated consistently across all disciplinary analysis modules. Figure 4 summarizes the data required to perform component placement analysis at each parametrization level. It is kept generic to allow flexible implementation in various tool-specific environments. The detailed implementation for the ACI-OPT framework is described in Section 4.5. The exact disciplinary parameters required to perform the systems integration analyses are specified in Tables 1 and 2 of Section 4.3.

In the conceptual design phase, geometric simplifications are used to reduce model complexity, simplify the development effort of the analysis tools, and improve computational performance, while preserving the level of detail required for the intended analysis fidelity. Equipment bays and components are represented as simplified geometric primitives, such as axis-aligned cuboids and cylinders. More detailed equipment bay geometries can be represented in the stereolithography (STL) format

when required by certain analyses, such as the component accessibility analysis for maintenance, where the equipment bay geometry can significantly impact the results.

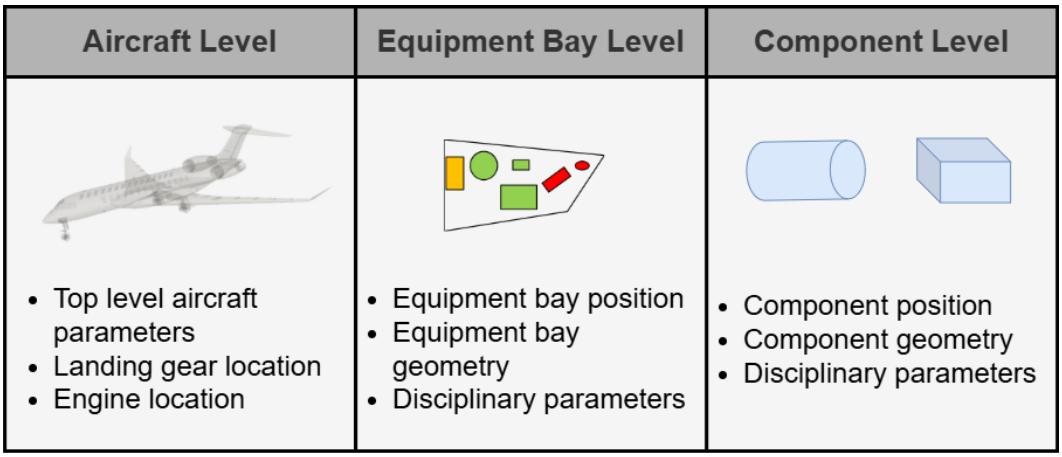


Figure 4 – Hierarchical structure of the standardized aircraft parametrization.

4.3 Integration of the Disciplinary Analysis Modules

The ACI-OPT framework builds on discipline-specific analysis methodologies developed in prior work to evaluate component layouts with respect to their main system integration constraints. This section focuses on the thermal, maintenance, and safety analysis modules, as these are the disciplines that are currently used to develop improved component layouts. Each analysis module implements a conceptual-level methodology that generates discipline-specific integration metrics from the standardized input data described in Section 4.2. These modules are not intended to replace the high-fidelity analyses required in later design phases, but rather to enable rapid system integration assessments at a level of precision consistent with the information available during conceptual design. The resulting outputs can be used as decision-support criteria by engineers or within an automated component placement workflow. This section does not describe the existing methodologies in detail, but instead summarizes how each analysis module is used to evaluate component layouts and support the development of improved design solutions. Detailed descriptions of the individual analysis methods are available in their respective publications.

4.3.1 Thermal Risk Assessment

The thermal risk assessment (TRA) evaluates the thermal aspects of equipment bays and their components during conceptual design [17–20]. *Thermal risk* is defined as the risk of a component failing to meet its thermal requirements, such as by exceeding its maximum allowable skin temperature. The TRA uses equipment bay, component, and operating case data to evaluate the main thermal integration aspects that are affected by component placement, as summarized in Table 1. These aspects are represented by individual thermal risk (TR) scores, which indicate the factors contributing to the thermal behavior of each component. The individual scores are consolidated to classify the thermal risk of each component as low, medium, or high. For components with a medium or high thermal risk, the individual scores can be used to identify the factors driving the thermal risk and guide the corresponding design modifications, as described in Section 4.4.

4.3.2 Maintenance Risk Assessment

The maintenance risk assessment (MRA) is used to evaluate the maintainability of aircraft system components located within equipment bays during conceptual design [21, 22]. *Maintenance risk* represents the potential difficulty of performing maintenance tasks on a component or within an equipment bay, which could lead to longer maintenance time and increased costs. The MRA uses equipment bay and component data to evaluate maintenance-related integration aspects at the component, intercomponent, and bay levels, as summarized in Table 2. These aspects are represented by individual maintenance risk (MR) scores, which are consolidated to classify the maintenance risk of each component as low, medium, or high. Within the component placement framework,

Table 1 – Summary of thermal risk assessment inputs, analysis criteria, and outputs.

Inputs to the TRA Module		TRA Analysis Criteria and Outputs	
Equipment Bay Level		**Equipment Bay Level**	
Geometry	Shape, position, size, orientation	Ventilation regime	TR_1
Ventilation	Number of sources, flow temperature, mass flow rate	Temperature stratification	TR_2
Component Level		**Component Level**	
Geometry	Shape, position, size, orientation	Mainstream flow	TR_3
Discipline-specific	Heat dissipation, temperature limit	Temperature limit	TR_4
		System integration	TR_5
Operating Case		Heat removal potential	TR_6
Altitude, ambient temperature, humidity, speed			

the intercomponent-level scores are the most relevant because they depend directly on the relative position of components and their accessibility within the equipment bay. The configuration score is the main indicator used to assess the effect of component placement on maintainability. This score evaluates whether components with the most challenging maintenance characteristics are also the most accessible within the equipment bay. Section 4.4 describes how the individual scores are used to guide the development of improved design solutions with respect to maintenance aspects.

Table 2 – Summary of maintenance risk assessment inputs, analysis criteria, and outputs.

Inputs to the MRA Module		MRA Analysis Criteria and Outputs	
Equipment Bay Level		**Component Level**	
Geometry	Shape, position, size, orientation, or STL file	Servicing rate	MR_1
		Connections	MR_2
Access panel	Number, position, size	Weight	MR_3
Component Level		**Intercomponent Level**	
Geometry	Shape, position, size, orientation	Accessibility	MR_4
		Configuration	MR_5
Discipline-specific	Mean time between failures, connections, weight	Operating space	MR_6
		Bay Level	
		Equipment bay shape	MR_7
		Access panel sizing	MR_8

4.3.3 Safety Assessment

The safety module integrated into the ACI-OPT framework considers the conceptual-level zonal safety analysis (CZSA) and the conceptual-level particular risk analysis (CPRA) developed in prior work [23, 24, 36], based on principles outlined in SAE ARP4761A [37]. The CZSA evaluates safety-related interactions that could arise from the equipment bay characteristics and component intrinsic risks. Critical interactions between components in an equipment bay and between components and the equipment bay itself are mapped and translated into zonal risk scores, enabling zonal safety risks to be identified. In the current implementation of the ACI-OPT framework, components are assigned to specified equipment bays and can only be repositioned within their assigned bay. As a result, the CZSA is not currently used to inform component placement. Future work will enable component relocation between equipment bays, allowing CZSA results to be considered in the component placement process.

The CPRA defines the threat envelopes associated with engine rotor bursts according to Advisory Circular 20-128A [38], and tire debris and wheel rim release according to Acceptable Means of Com-

pliance 25.734 [39]. Components located within these threat envelopes are automatically identified, and design precautions such as removal from the zone or component segregation can be implemented based on the safety-criticality of the affected components and their functional relationships. An example of a rotor burst threat zone is illustrated in the AEB application case in Section 5.3.

4.4 Layout Evaluation and Design Space Exploration

The main objective of the ACI-OPT framework is to evaluate baseline component layouts and systematically improve them according to their system integration characteristics. The layout evaluation and DSE procedures use the outputs of the disciplinary analysis modules to identify the main integration issues with a given configuration and propose design improvements that are tailored to these issues. As the applicable design modifications strongly depend on the equipment bay configuration, the procedure is presented separately for each type of equipment bay considered in this work. The following subsections describe the approaches used to develop improved layouts for the FAR, UEB, and AEB.

4.4.1 Avionics Rack

As mentioned in Section 2, the placement of the components in the FAR is primarily driven by the TRA. As such, the DSE procedure begins by decomposing the thermal risk scores of the highest-risk components into the individual thermal risk scores shown in Table 1. Design solutions are proposed according to the main factors driving the thermal risk of the components of interest. Figure 5 summarizes the sequential DSE process for the avionics rack. The aim is to achieve a bay configuration with

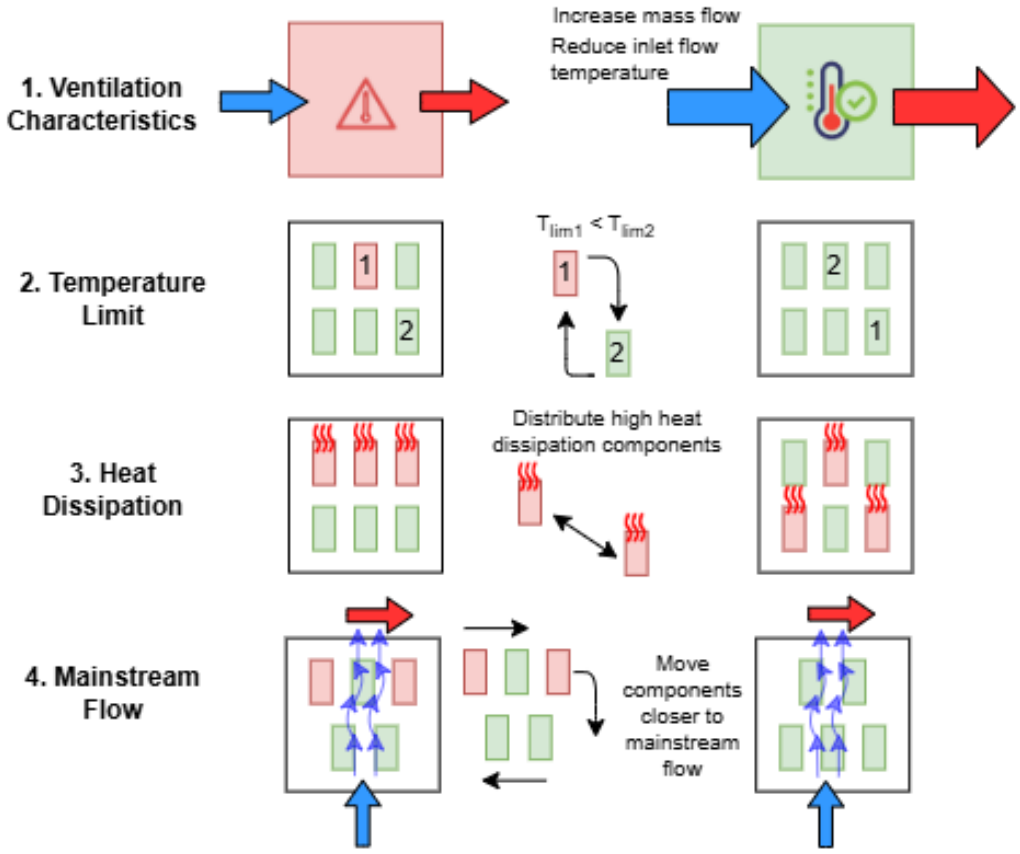


Figure 5 – Design space exploration procedure for the avionics rack (T_{lim}: component temperature limit).

no high-risk components, as these indicate an infeasible solution. The DSE procedure is applied as follows:

1. If the thermal risk is primarily driven by the equipment bay-level scores, the ventilation characteristics are insufficient to sufficiently cool the installed components. In such a case, the inlet

mass flow rate can be increased, the inlet flow temperature can be decreased, or the number of components in the rack can be reduced. In practice, reducing the cooling flow temperature is generally not feasible, and reducing the number of components in the rack may not be possible. The cooling mass flow can be increased, but this has implications at the system and aircraft levels that are outside the scope of this work.

2. If the thermal risk of a component is primarily driven by its temperature limit score, its maximum allowable temperature is compared with the maximum allowable temperature of the other components in the rack. If possible, the layout is modified by swapping components, placing the more thermally sensitive component at the bottom of the rack, closer to the inlet.

3. If the thermal risk is driven by the heat removal potential score, the layout is modified to reduce local concentrations of heat dissipation. Components with high heat dissipation are redistributed to avoid clustering in the same region of the rack. This balances the cooling load between different regions and prevents the cooling flow from being heated excessively in a localized area.

4. If the thermal risk is driven by the mainstream flow score, the component position is evaluated relative to the main cooling flow path in both the streamwise and cross-stream directions. Components with high mainstream flow scores are repositioned closer to the inlet or closer to the main cooling flow path, where geometrically possible. This may be achieved without penalizing other components when the components on upper shelves extend farther toward the rack side walls than those on lower shelves, either because of their geometry or because more components are installed on the shelf. In this case, the shelves are rearranged to position the components located farther from the rack centerline with a high cross-stream number closer to the inlet, reducing the streamwise contribution to the mainstream flow score.

Although many of the proposed design modifications involve moving high-risk components to lower shelves, this may not always be possible or beneficial. The number of positions in the lower shelves is limited, so some components must inevitably be located in the upper shelves. In addition, placing higher heat dissipation components near the inlet increases the cooling flow temperature earlier in the rack, reducing the cooling effectiveness for downstream components. As such, the TRA is re-evaluated after each proposed modification, and the new layout is retained only if it reduces the overall thermal risk of the components in the rack. If medium or high thermal risk components remain after the layout modifications, broader design changes may be required, such as adjusting the ventilation parameters, reducing the number of components in the rack, changing the nature of the components in the rack, or introducing local active cooling for selected components.

4.4.2 Underfloor Equipment Bay

In accordance with Section 2, the DSE procedure for the UEB consists of arranging the components to favor maintainability, while the ventilation parameters are varied to determine the minimum cooling flow requirements to achieve a thermally feasible configuration.

Among the maintenance risk scores presented in Table 2, the configuration score, MR_5, is the primary driver of component placement. This score evaluates whether the components with the least favorable maintenance characteristics are the most accessible. The component-level maintenance aspects are determined through the component-level scores, namely the servicing rate score, MR_1, the type of connections score, MR_2, and the weight score, MR_3. Because all components in the UEB can be accessed without removing any other components, component accessibility is determined by their distance from the access panel. In the current implementation, all component-level scores are weighted equally. From a maintenance perspective, the optimal configuration contains components arranged according to their component-level scores, such that the distance of the component from the access panel increases as the sum of their component-level scores decreases. This is shown in Equation 1, where S is the sum of the component-level maintenance risk scores, d is the distance of a component from its nearest access panel, and the subscripts i and j represent independent

components. This approach ensures that the components with the least favorable maintenance characteristics are placed closest to the access panel.

$$S_i = MR_{1,i} + MR_{2,i} + MR_{3,i}, \qquad S_i > S_j \Rightarrow d_i < d_j \tag{1}$$

With the component layout arranged to favor maintainability, the ventilation characteristics are varied to determine the minimum requirements for the cooling flow parameters. A parametric sweep is performed over the inlet flow temperature and mass flow rate to identify the combinations that achieve the desired thermal risk classification. For instance, these parameters can be varied within defined ranges to determine which combinations eliminate high thermal risks for all components, as shown in Equation 2, where D_{vent} is the design space of the ventilation parameters, T_{in} is the inlet flow temperature, and $\dot{m}_{in}$ is the inlet mass flow rate.

$$D_{vent} = \left\{ (T_{in}, \dot{m}_{in}) \mid T_{in}^{min} \leq T_{in} \leq T_{in}^{max}, \quad \dot{m}_{in}^{min} \leq \dot{m}_{in} \leq \dot{m}_{in}^{max} \right\} \tag{2}$$

Alternatively, additional ventilation sources could also be introduced to improve the thermal behavior of the components in the UEB. However, this is not considered in the automated ACI-OPT framework, because the placement of additional ventilation sources is an open design problem that requires further knowledge of installation constraints, implications on the air systems, routing considerations, weight penalties, and other system- and aircraft-level effects. These considerations will be addressed in future work.

4.4.3 Aft Equipment Bay

The AEB component placement procedure is the most complex among the equipment bays of the notional business jet aircraft considered in this work, as discussed in Section 2. To adequately survey the design space and consider the coupling between system integration disciplines, formal optimization approaches are required. However, this represents ongoing work and is not currently supported within the ACI-OPT framework.

A grid-based relocation procedure is introduced as an initial DSE approach for the AEB. The available installation volume is discretized into evenly distributed nodes that represent possible component positions within the bay, as illustrated in Figure 6. High-risk components are moved to the nearest node one at a time, while keeping all other component positions fixed.

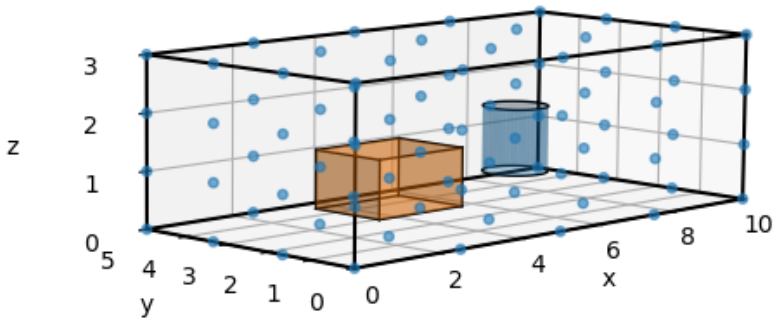


Figure 6 – Grid discretization of a simplified geometry for the aft equipment bay component relocation procedure.

The relocation procedure is summarized in Figure 7. At each new candidate position, the component of interest is first checked for geometric overlap with the other components in the bay. If no overlap is detected, it is evaluated according to each system integration discipline considered in increasing order of runtime. If an analysis returns an unacceptable result, the candidate node is rejected, and the component is moved to the nearest available node. If all criteria are satisfied, the configuration is deemed feasible. This process is repeated for all high-risk components until a feasible configuration has been identified and the search is terminated, or until all nodes have been evaluated.

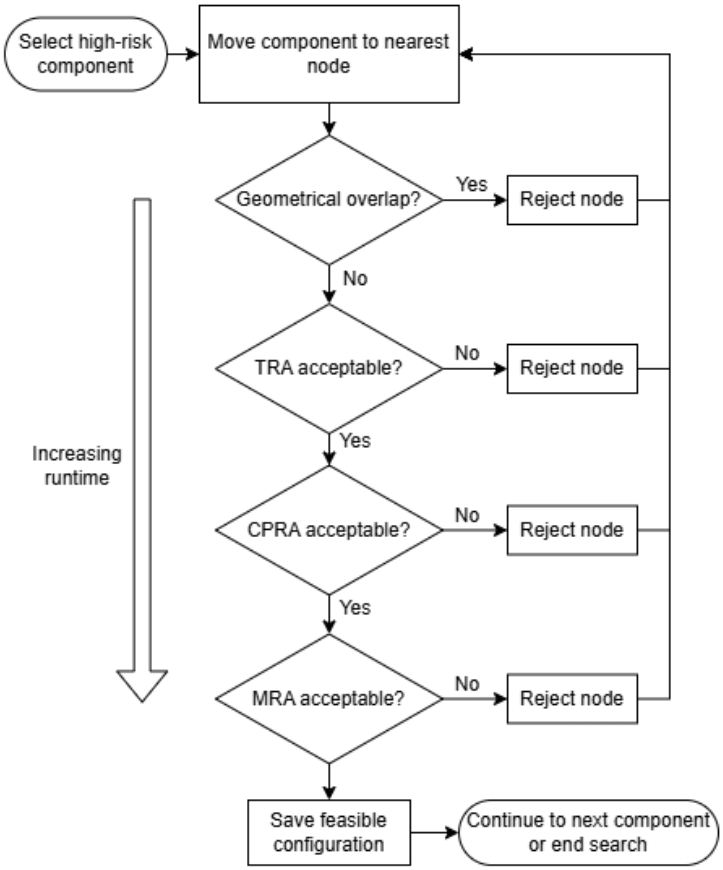


Figure 7 – Aft equipment bay grid-based relocation procedure.

This relocation procedure provides a practical way to improve selected AEB component positions using the current capabilities of the framework. However, it remains limited because it evaluates components sequentially and does not fully explore the coupled design space. In addition, the procedure is computationally inefficient and does not include a guided search strategy to identify promising candidate positions, making it scale poorly and rendering it impractical for configurations with many high-risk components and more complex layouts. The current approach also assumes that components can be moved to any available grid point, which may not be realistic when structural mounting, installation interfaces, or routing constraints are taken into account. These placement restrictions can be partially considered by limiting the available grid points, but a more complete treatment requires integrating structural and routing aspects, which will be addressed in future work.

4.5 Implementation Aspects

Thus far, the component placement framework has been described in an implementation-agnostic manner, such that the proposed methodology is not limited to a specific programming language or software architecture. The framework establishes a generalized workflow in which disciplinary analysis modules evaluate component layouts using data available at the conceptual design stage. The present implementation, summarized in Figure 8, is provided to illustrate the practical realization of the methodology.

The framework is implemented in Python using an object-oriented programming (OOP) approach. A standalone *Geometry* package defines the core geometric data structures and operations required by the analysis modules. The base *Geometry* class defines a generic geometric object through the minimum set of attributes required to describe its spatial properties, namely its position, size, and orientation. The class also provides fundamental geometric operations such as translation, rotation, and scaling. The *Cylinder* and *Cuboid* classes are built on the *Geometry* class using inheritance to define primitive solid objects. These classes extend the base *Geometry* class with shape-specific

methods that are required by the analysis modules. These include the generation of bounding boxes, the discretization of solids into point clouds, the calculation of the surface area and volume of the object, and additional shape-specific operations.

The *AircraftZone* and *Component* classes extend the primitive solid objects defined in the *Cylinder* and *Cuboid* classes to real physical entities in the aircraft. The classes hold an attribute that specifies their primitive solid shape, which enables shape-specific operations to be performed using the *Cylinder* or *Cuboid* class.

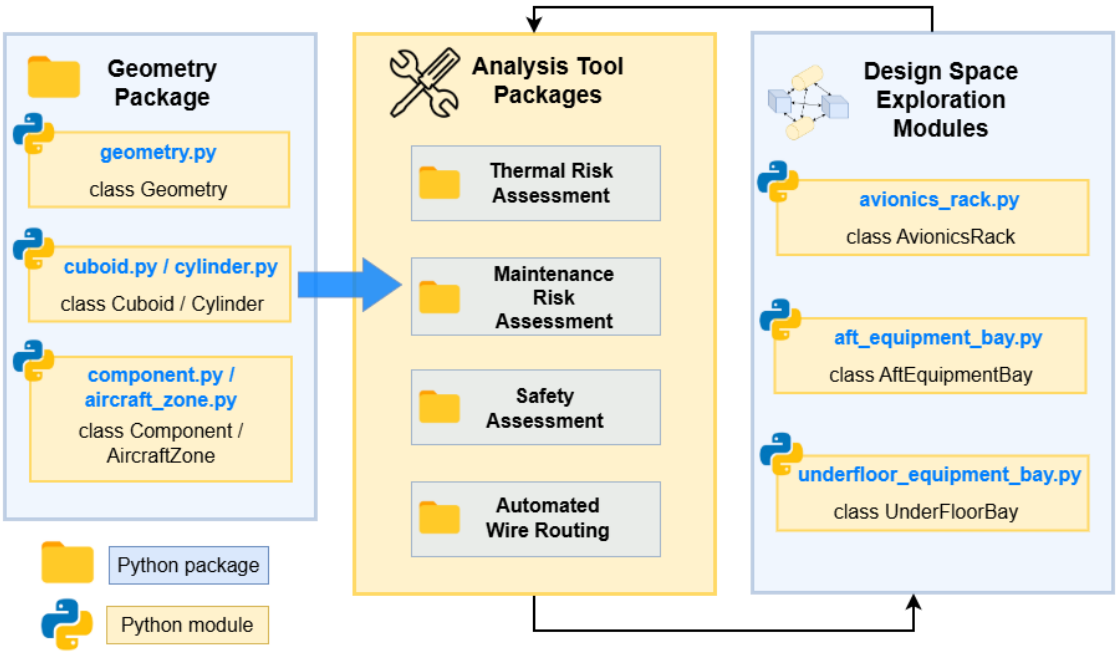


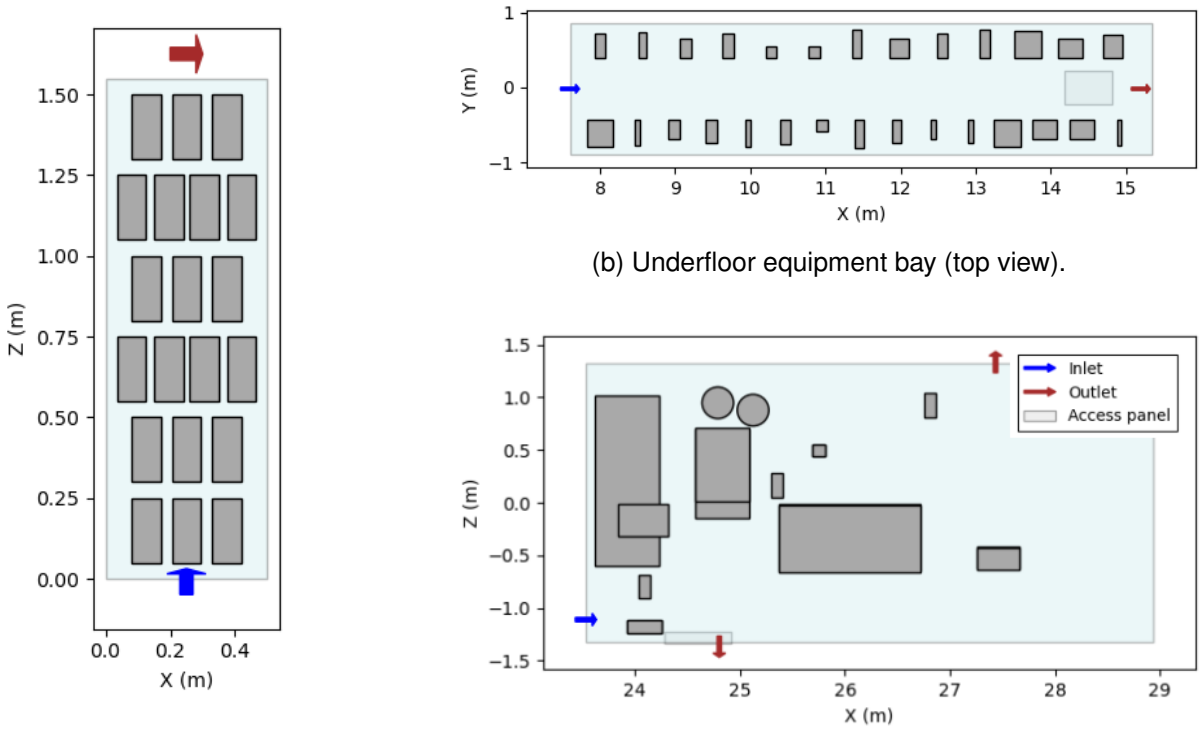
Figure 8 – ACI-OPT framework code organization.

The disciplinary analysis tools also use an OOP approach in Python. The *Geometry* package is a dependency for each of the analysis tools, as it provides the classes from which the objects used in the disciplinary analyses are instantiated. After execution of the analysis tools, the results are passed back to the plotting functions of the *Geometry* package to display them using the Matplotlib library or the Engineering Sketch Pad parametric modelling software [40].

The overall component placement workflow is managed by the *ACI-OPT* package that integrates the *Geometry* package and the individual disciplinary analysis tools. The package handles input/output operations and initializes the aircraft configuration according to the standardized parametrization. It establishes the link between the aircraft parametrization obtained as an input, the initialization of the parametric aircraft geometry, the execution of the analysis tools, and the processing of the outputs. The *ACI-OPT* package also supports the repeated evaluations of modified component layouts, as required by the DSE procedures described in Section 4.4.

5 Application Cases

The ACI-OPT framework is applied to a conventional, notional business jet aircraft featuring aft-mounted engines and a tricycle landing gear arrangement, as illustrated in Figure 2. Simplified representations of the FAR, UEB, and AEB are depicted in Figure 9, including the baseline component locations, ventilation sources, and access panels. The thermal behavior, maintainability, and particular risk threat envelopes of the baseline configurations are evaluated using the TRA, MRA, and CPRA. The DSE methods are used to improve the component layouts in each equipment bay.



(a) Avionics rack (side view).

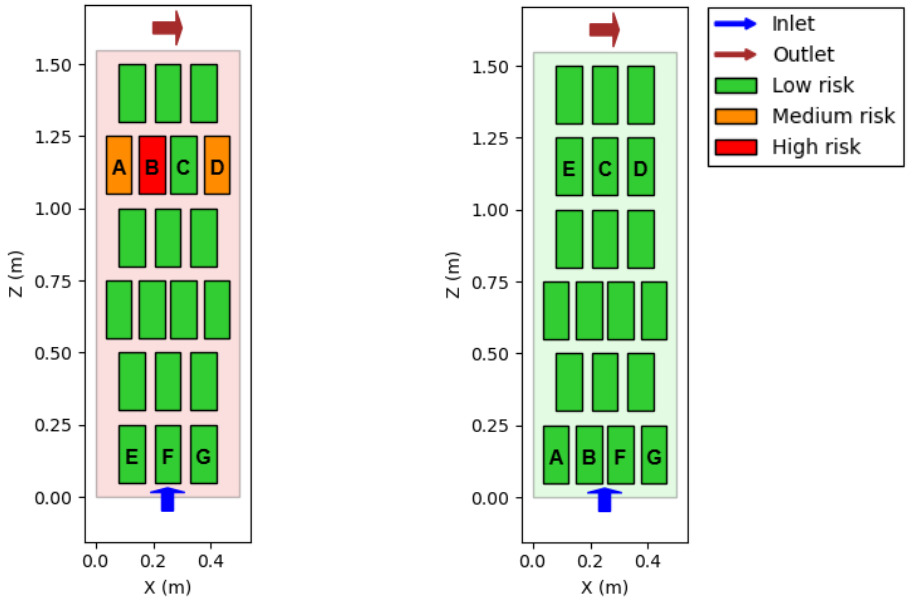
(b) Underfloor equipment bay (top view).

(c) Aft equipment bay (side view).

Figure 9 – Equipment bay configurations.

5.1 Forward Avionics Rack

The FAR in Figure 9a contains 20 avionics and electronic LRUs distributed across 6 shelves. The cooling of components is achieved by air entering the inlet at the bottom of the rack and exiting through the outlet at the top. All components are directly accessible for maintenance via the rack's front panel. As the components have similar maintenance characteristics and the rack is not contained in a particular risk zone, this example focuses only on thermal aspects. The results of the TRA are depicted in Figure 10.



(a) Baseline configuration.

(b) Improved configuration.

Figure 10 – Avionics rack thermal risk assessment results and layout improvement (side view).

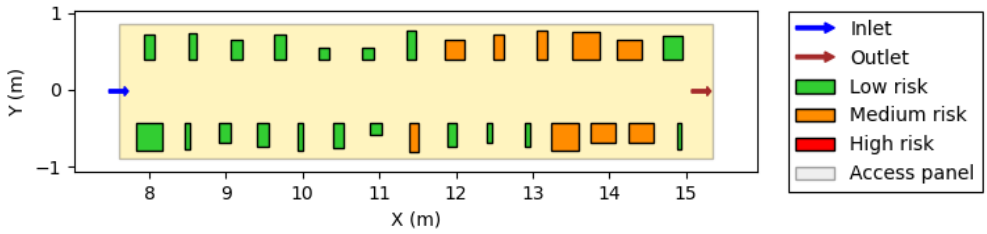
Figure 10a shows that the original layout contains one high-risk component, B, and two medium-risk components, A and D, all located in the upper portion of the rack. The thermal risk of component B is mainly driven by its stricter temperature limit. Its maximum allowable temperature is $55\ ^{\circ}\mathrm{C}$, compared to $70\ ^{\circ}\mathrm{C}$ for all other components in the rack. Using the DSE procedure described in Section 4.4.1, component B is swapped with component E on the lower shelf, where the air temperature is lower and component B is closer to the cooling inlet. This reduces the thermal risk of component B to low, while component E remains at a low risk level because of its higher allowable temperature, as shown in Figure 10b.

The DSE procedure is also applied to the medium-risk components A and D. Their thermal risks are mainly driven by the mainstream flow score, because their original shelf contains more components and places them far from the main cooling flow path and also far from the inlet. The DSE procedure captures this effect and relocates one component from the second-highest shelf to the bottom of the rack, where the cooling conditions are more favorable. The resulting layout reduces the thermal risks of components A, B, and D, yielding a configuration in which all components have a low thermal risk.

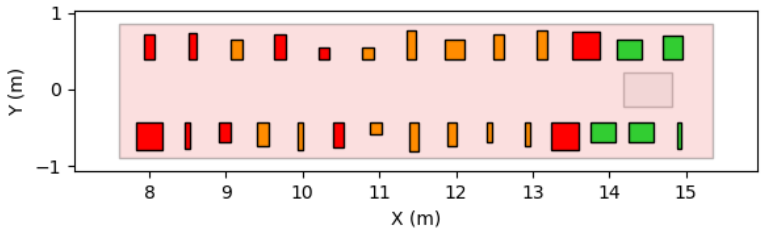
5.2 Underfloor Equipment Bay

The UEB in Figure 9b contains avionics and electronic LRUs distributed on either side of a central aisle. Cooling air enters the equipment bay in the forward part of the bay and exits in the aft portion of the bay. The bay can be entered through a hatch in its aft portion to access the components for maintenance. The central aisle serves as a crawl space, allowing maintenance technicians to reach components in the forward part of the bay.

Figure 11a shows that the UEB contains several medium thermal-risk components because the ventilation parameters are insufficient to adequately cool the downstream components. The UEB also contains several components with medium or high maintenance risks because the components are not arranged according to their component-level maintenance characteristics in the baseline layout.



(a) Thermal risk assessment.



(b) Maintenance risk assessment.

Figure 11 – Underfloor equipment bay system integration analyses (top view).

The high maintenance risks are mainly driven by the servicing rate score, MR_1, and the configuration score, MR_5. As MR_1 depends on the component mean time between failures (MTBF), it cannot be reduced without modifying the physical architecture. The layout improvement, therefore, focuses on MR_5, which depends directly on component placement. The DSE procedure of Section 4.4.2 is applied to position components based on their component-level maintenance attributes, reducing the number of components with a medium configuration risk score from 10 to 6 while keeping all components below a high risk score.

A parametric sweep of the inlet flow temperature and mass flow rate was performed on the layout arranged to favor maintainability to determine the ventilation parameters required to obtain a thermally feasible configuration. Figure 12 shows that the average thermal risk decreases as the inlet flow temperature decreases and the mass flow rate increases, as expected. The process identifies the combinations of ventilation parameters required to eliminate high thermal risks, as well as the combinations for which all components have a low thermal risk. These results define the minimum cooling flow requirements for the UEB according to the desired thermal risk classification.

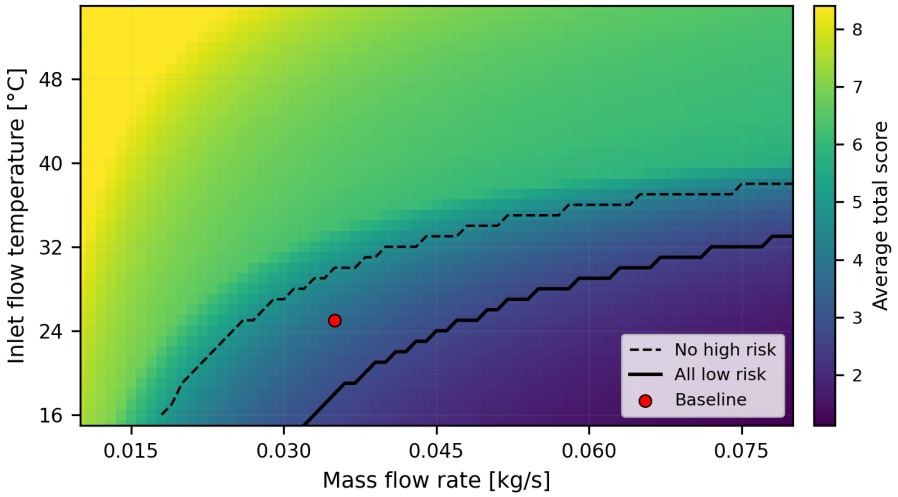


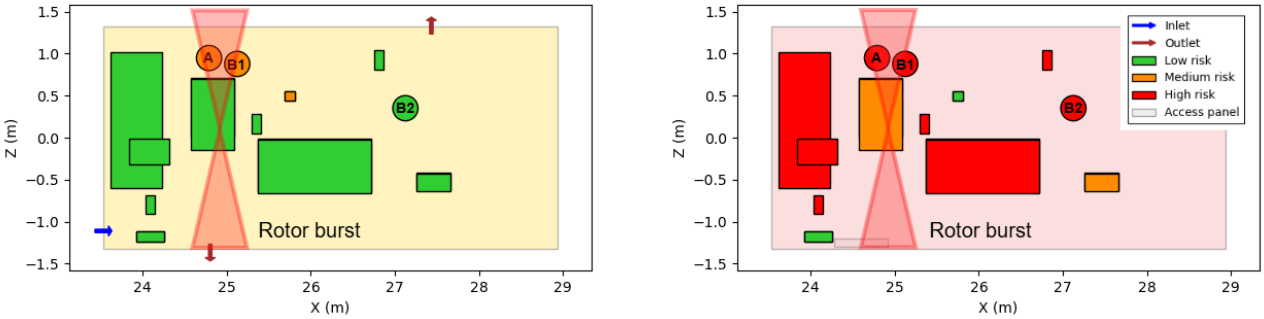
Figure 12 – Average thermal risk score of underfloor equipment bay components for varied mass flow rate and inlet flow temperature.

5.3 Aft Equipment Bay

The AEB in Figure 9c contains several types of components distributed across the available installation volume. Cooling flow enters at the forward end of the bay and exits through outlets located at the top, bottom, and sides of the bay. Maintenance access is provided through a hatch at the bottom of the bay. Figure 13 shows the TRA and MRA results with the overlaid rotor burst risk zones for the AEB. Four components exhibit medium thermal risks, while several components have high maintenance risks. The high maintenance risks are caused by the complex connection types of the components in the AEB and by components with lower MTBF being obstructed by components with higher MTBF. The initial layout also places redundant components within the same engine rotor burst zone.

Component B is selected for relocation because it has a medium thermal risk and is located in the same engine rotor burst zone as component A, which shares the same function. Using the grid-based relocation procedure described in Section 4.4.3, a new position is identified in the aft section of the AEB, as indicated by the $B2$ label in Figure 13. The relocation reduces the thermal risk of the component by placing it closer to a ventilation source and in a less densely populated region of the bay. It also removes component B from the rotor burst zone, eliminating the risk associated with positioning two components that share a function within the same threat envelope.

The MRA of the AEB illustrates an important limitation of the current DSE approaches implemented in the ACI-OPT framework. In the AEB, the maintenance risk depends on the accessibility of each component relative to all other components in the bay, resulting in a high-dimensional problem that cannot be effectively addressed with the grid-based DSE procedure. In addition, the MRA evaluates component accessibility using a parametric modeller in the loop, which significantly increases runtime and limits the number of configurations that can be evaluated. This motivates future work regarding the reduction of the MRA runtime and the integration of more systematic optimization methods for complex equipment bays.



(a) Thermal risk assessment.

(b) Maintenance risk assessment.

Figure 13 – Aft equipment bay system integration analyses and relocation of component B (side view).

6 Conclusion and Future Work

This paper introduces the ACI-OPT framework for automated aircraft system component placement during conceptual design. The framework integrates a standardized aircraft parametrization with thermal, maintenance, and safety analysis modules to enable the evaluation of component layouts based on their primary integration constraints. Targeted DSE procedures use these disciplinary outputs to identify integration issues and generate improved configurations. The methodology was demonstrated on an avionics rack, an underfloor equipment bay, and an aft equipment bay of a notional business jet. The results show that the approach supports the assessment of layout feasibility, enables the systematic improvement of component placement, and highlights the increasing complexity of integration problems in more strongly coupled environments such as the aft equipment bay.

Future work will focus on extending the framework to fully integrate all system integration disciplines, enable component placement across multiple equipment bays, and incorporate routing and structural considerations. Improvements in computational performance, particularly for maintenance assessment, are required to increase scalability. In addition, integrating optimization methods will enable a more systematic exploration of the design space beyond the current DSE procedures. Overall, the ACI-OPT framework provides a foundation for earlier and more systematic assessment of aircraft systems integration, supporting the evaluation of novel configurations and architectures while reducing the risk of late-stage design changes.

7 Acknowledgments

This work is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Consortium de recherche et d'innovation en aérospatiale au Québec (CRIAQ), Bombardier, MTLS Aerostructure, and Stream Systems through a joint research project with grant number ALLRP 576486 - 22. The authors acknowledge the contributions of Bombardier in developing the notional business jet equipment bay configurations and the valuable technical insights of Ali Tfaily.

8 Contact Author Email Address

Mail to: Joey Vézina: joey.vezina@mail.concordia.ca or
Susan Liscouët-Hanke: susan.liscouet-hanke@concordia.ca

9 Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.

References

[1] International Air Transport Association. Net zero carbon 2050 resolution – fact sheet. https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet-iata-net-zero-resolution/, 2021. Accessed: 03 December 2025.

[2] Benad J and Vos R. Design of a flying v subsonic transport. In *Proceedings of the 33rd Congress of the International Council of the Aeronautical Sciences*, Stockholm, Sweden, September 2022.

[3] Larrimer B I. *Beyond tube-and-wing: The X-48 blended wing-body and NASA's quest to reshape future transport aircraft*. NASA Aeronautics Book Series. National Aeronautics and Space Administration, Washington, DC, 2020.

[4] Wells D P, Gatlin G M, June J C, and Marien T V. Nasa transonic truss-braced wing studies. In *Proc of the 34th Congress of the International Council of the Aeronautical Sciences*, Florence, Italy, 2024.

[5] Beschorner K, Kriewall V, Bielsky T, and Thielecke F. Conceptual design and energy management analysis of turbofan-based hybrid-electric propulsion. *Journal of Aircraft*, 62(6):1665–1679, 2025.

[6] Brelje B J and Martins J R R A. Electric, hybrid, and turboelectric fixed-wing aircraft: a review of concepts, models, and design approaches. *Progress in Aerospace Sciences*, 104:1–19, 2019.

[7] Leitão A B V, Bringhenti C, Tomita J T, Silva F J S, Xisto C, and Grönstedt T. A review of hydrogen aircraft propulsion systems: recent advances and environmental perspectives. *International Journal of Hydrogen Energy*, 176:151489, 2025.

[8] Chakraborty I, Mavris D N, Emeneth M, and Schneegans A. A methodology for vehicle and mission level comparison of more electric aircraft subsystem solutions: application to the flight control actuation system. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 229(6):1088–1102, 2015.

[9] Sanchez F, Liscouët-Hanke S, and Tfaily A. Improving aircraft conceptual design through parametric cad modellers - a case study for thermal analysis of aircraft systems. *Computers in Industry*, 130:103467, 2021.

[10] Kriewall V, Herrmann J, and Thielecke F. Interactions and synergies between aircraft on-board systems and hydrogen turbofans. In *AIAA SciTech 2025 Forum*, Orlando, United States, 2025.

[11] Vankan W J, Maas R, and Moghadasi S M. Optimization tool for equipment placement and routing in more electric aircraft. Royal Netherlands Aerospace Centre, Online Report, 2020.

[12] Fuchte J, Nagel B, and Gollnick V. Automatic fuselage system layout using knowledge based design rules. In *Proc Deutscher Luft- und Raumfahrtkongress*, Berlin, Germany, 2012.

[13] Liscouet-Hanke S, Tfaily A, and Esdras G. Parametric 3d modeling for integration of aircraft systems in conceptual design. In *Proceedings of the 62nd CASI Aeronautics Conferences*, Montreal, Canada, 2015.

[14] Vézina J and Liscouët-Hanke S. Initial systems layout and safety analysis for the flying-v aircraft. In *AIAA Regional Student Conferences*, Montreal, Canada, 2025.

[15] Kuelper N, Broehan J, Bielsky T, and Thielecke F. Systems architecting assistant (sara) – enabling a seamless process chain from requirements to overall systems design. In *Proceedings of the 33rd Congress of the International Council of the Aeronautical Sciences*, Stockholm, Sweden, 2022.

[16] Bielsky T, Kuelper N, and Thielecke F. Overall parametric design and integration of on-board systems for a hydrogen-powered concept aircraft. In *Aerospace Europe Conference 2023 – 10th EUCASS – 9th CEAS*, Lausanne, Switzerland, 2023.

[17] Sanchez F, Liscouet-Hanke S, Beaulac S, and Boutin A. A thermal risk assessment approach for the conceptual design of aircraft system architectures. In *AIAA Aviation Forum*, Dallas, United States, 2019.

[18] Sanchez F and Liscouet-Hanke S. Thermal risk prediction methodology for conceptual design of aircraft equipment bays. *Aerospace Science and Technology*, 104:105946, 2020.

[19] Sanchez F, Huzaifa A M, and Liscouet-Hanke S. Ventilation considerations for an enhanced thermal risk prediction in aircraft conceptual design. *Aerospace Science and Technology*, 108:106401, 2021.

[20] Huzaifa A M. *System-level ventilation considerations for thermal risk assessment of aircraft systems in conceptual design*. Master's thesis, Concordia University, 2021.

[21] Sélim S, Liscouet-Hanke S, Tfaily A, Butt A, and Alphonso B. Scoring approach to assess maintenance risk for aircraft systems in conceptual design. *Journal of Aircraft*, 60(5):1577–1587, 2023.

[22] Muyenzikazi N and Liscouet-Hanke S. Automation of aircraft maintenance risk assessment using a parametric geometry modeler. In *Proc AIAA Aviation Forum*, Las Vegas, United States, 2025.

[23] Bamrah P, Liscouet-Hanke S, Tfaily A, and Tamayo A. Zonal safety and particular risk analysis for early aircraft design. *Journal of Aircraft*, 62(2):254–269, 2025.

[24] Bamrah P. *Zonal safety and particular risk analysis for early aircraft design using parametric geometric*

modelling. Master's thesis, Concordia University, 2023.

[25] Setty B L and Liscouet-Hanke S. Automation of wire routing for aircraft conceptual design. In *Proc AIAA SciTech Forum*, Orlando, United States, 2026.

[26] Mahdi A. Bombardier global 7500 3d model. `https://sketchfab.com/3d-models/bombardier-global-7500-08c977705e4b473bb0539b32a86a6c27`, October 2025.

[27] Şahin B and Oliva M. A new approach for aircraft equipment layout design process. In *Product Lifecycle Management (PLM 2025), IFIP Advances in Information and Communication Technology*. Springer Nature Switzerland. Vol. 773, pp 88–97, 2026.

[28] Fioriti M, Hansmann P, and Torrigiani F. Certification driven stream mdo framework descriptions and trade of results. Technical report, 2021.

[29] Xue L, Zhou D, and Zhou W. Research of aircraft equipment cabin layout optimization methods based on virtual maintenance. In *Proc 11th International Conference on Reliability, Maintainability and Safety (ICRMS)*, Hangzhou, China, 2016.

[30] Luo X, Yang Y, Ge Z, Wen X, and Guan F. Layout problem of multi-component systems arising for improving maintainability. *Journal of Central South University*, 21(5):1833–1841, 2014.

[31] Cuco A, Sousa F, and Silva Neto A. A multi-objective methodology for spacecraft equipment layouts. *Optimization and Engineering*, 16(1):165–181, 2015.

[32] Torrigiani F, Deinert S, Fioriti M, Fede F, Jungo A, Pisu L, Sanchez F, Liscouet-Hanke S, Ciampa P D, and Nagel B. An mbse certification-driven design of a uav male configuration in the agile 4.0 design environment. In *Proc AIAA Aviation Forum*, Virtual event, 2021.

[33] Ng T and Leng G. Design of small-scale quadrotor unmanned air vehicles using genetic algorithms. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 221(5):893–905, 2007.

[34] Lee K, Kang N, Kokkolaras M, and Papalambros P. Design optimisation of a hybrid electric vehicle cooling system considering performance and packaging. *International Journal of Vehicle Design*, 85(2-4):154–177, 2021.

[35] Miao Y, Fadel G, and Gantovnik V. Vehicle configuration design with a packing genetic algorithm. *International Journal of Heavy Vehicle Systems*, 15(2/3/4):433–448, 2008.

[36] Vézina J, Leccese L, and Liscouët-Hanke S. Overcoming the parametric modeler: a native python approach to the particular risk analysis (in press). In *AIAA Regional Student Conferences*, College Park, United States, 2026.

[37] Guidelines for conducting the safety assessment process on civil aircraft, systems, and equipment. Aerospace Recommended Practice 4761, Revision A, SAE International, 2023.

[38] Design considerations for minimizing hazards caused by uncontained turbine engine and auxiliary power unit rotor failure. Technical Report Advisory Circular AC 20-128A, Federal Aviation Administration, March 1997.

[39] Protection against wheel and tyre failures. Acceptable Means of Compliance 25.734, European Aviation Safety Agency, Revision from January 2023.

[40] Dannenhoffer J F. An overview of the engineering sketch pad. In *AIAA SciTech Forum*, Orlando, United States, 2024.