Automatic Fuselage System Layout using Knowledge Based Design Rules

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Abstract

This paper introduces a tool for preliminary system placement inside an aircraft's fuselage. Objective is to estimate the effect of design decisions on system routing, which may then be used for better weight estimation or physical modeling. The method uses a detailed geometrical model of the fuselage including cabin and primary structure. The system components and connectors are placed according to knowledge patterns. The focus is on large fuselage systems such as the environmental control system, the water&waste system and parts of the electrical system, which are the most significant in terms of size and weight.

Abbreviations

AC	Alternating Current
APU	Auxiliary Power Unit
CPACS	Common Parametric Aircraft Configuration Scheme
DC	Direct Current
DMU	Digital Mock-Up
ECS	Environmental Control System
EPS	Electrical Power System
FCS	Flight Control System
MOA	More Electric Architecture resp. Aircraft
WWS	Water&Waste System
PC	Power Center

1 Introduction

This section outlines the motivation and scope of the work. Further recent publications concerning the subject are listed.

1.1 Motivation

System architecture in current aircraft design follows long established patterns. It is of major importance for the design of the fuselage as the systems affect the overall arrangement of it. Cabin and cargo hold occupy the majority of space inside the pressurized fuselage, leaving only scarce fractions of the space for system components and routing.

Systems are consequently placed whereever they fit best, while some systems are more flexible than others when it comes to location. Some can be placed with small penalty anywhere in the fuselage, for example electronic system components. Other systems are more constrained.

Systems such as the environmental control system (ECS), the water&waste system (WWS) and the electrical power system (EPS) have substantial requirement for connectors and ducts. These connectors and ducts may transport electricity, water or compressed aircraft. They occupy a substantial volume inside the fuselage and they reduce the effectiveness of the system itself through pressure loss or electric resistance. A better understanding of the effect of system component placement on the routing is desirable. A detailed routing may be useful for various aspects of aircraft design, for example:

1. The knowledge of discrete routes allows an estimation of the weight of these connectors and hence allows trade studies to find a multi-disciplinary optimum.
2. The routing influences the system's performance through pressure losses, which again influences system's weight and energy consumption.
3. Space inside the fuselage is limited and the arrangement of system connectors needs to adapt to changing aircraft configurations. Alternative system arrangements can be studied and assessed.

The introduced method studies the effect of changing architecture on fuselage design. The method creates a preliminary digital mock-up (DMU) that includes the systems with the highest requirement for volume. This allows to identify the a suitable architecture in early stages of the design. Possible applications include new system technology such as fuel cells, different engine location or new concepts like displacement ventilation. Another important information is the position of possible heat sources inside the fuselage that require cooling.

1.2 Scope of the Work

The introduced method creates a system architecture of the environmental control system, parts of the electrical power system and the water&waste system. This includes the position of major components, the route of ducts and other connectors and interfaces to the cabin or other parts of the airframe. The routes are found using an algorithm for identification of available space and a detailed model of the fuselage. The routes follow knowledge patterns for system placing based on current technology aircraft. The

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routing algorithm places connectors under consideration of available space inside a particular part of the fuselage. The routing is performed only in the pressurized part of the fuselage. Systems such as hydraulics or flight controls are excluded during this initial development step.
The tool is developed in Matlab. Even the standard plot functions allow a CAD-like visualization of the resulting system routing. A CAD-interface is not implemented but as shown in [12], an interface between Matlab and CATIA can be established quickly.

1.3 State of the Art

The estimation of system properties is well established in preliminary aircraft design. Depending on the purpose different modeling approaches exist. Several works published methods for estimation of aircraft system weight by using more advanced physical models. Koeppen [4] introduced such a method for preliminary aircraft design. Dollmayer [13] used advanced models to estimate the effect of system energy consumption on aircraft performance. A similar approach is pursued by Lammering [14] focusing on the energy consumption of the systems. Lüdders [9] studied the effect of a fuel cell. All mentioned works include the required energy of the system in their model. Geometrical properties are only partly considered. Koeppen considers the weight of the ducts and connectors.

Several other methods and tools exists. The introduced tool is hence not the first of its kind. The difference to existing tools and methods is that the routing is done fully automatic within a preliminary design loop. Hence it can be used to study the influence of overall aircraft design decisions on system design, and vice versa the influence of system design decision on aircraft performance. Currently such trade studies are performed using simplified CAD tools. The method can be understood as supplement for existing methods, introducing more information about the connectors and allowing a more precise modeling of the physical properties of the system.

System architecture is only partly covered in aircraft design textbooks. A notable exception is the fourth volume of Roskam's Aircraft Design series [10], which features sketches of system architecture for the B767 and some other designs.

2 System Architecture

This section explains the current state-of-the-art in system architecture and also indicates at which point future aircraft might deviate from this architecture.

2.1 General

System architecture describes the arrangement of the system components. Each system has a source. That is, it does receive something from a particular point of the aircraft. This may be pressurized air from the engine, ram air from an air inlet or electrical power or the fresh water from the fresh water tank. Each system then has components that process, distribute or rearrange the particular system's resource. These components can have boundary conditions concerning their position inside the fuselage. Each system further has sinks which locations are either dictated by the cabin and airframe arrangement or represent another degree of freedom for the system. In the following the sources, components and sinks are described for each of the three considered systems.

2.2 Environmental Control System - ECS

The Environmental Control System (ECS) is responsible for the provision of a survivable atmosphere inside the cabin. This includes the control of a minimum air pressure and the regulation of the temperature. As passengers add heat, water vapor and consume oxygen, the air inside the cabin needs to be recirculated, dehumidified and exchanged constantly. The ECS receives fresh air from outside the aircraft through ram air inlets. Heat and energy are taken from the engines' compressor as bleed air. The hot and cold air are mixed in the air conditioning packs, which are located outside the pressurized fuselage. The packs transmit the breathable air to the mixer unit, which also receives recirculated air from inside the cabin. From the mixer unit ducts lead to various parts of the cabin and end inside the cabin. The architecture of the ducts may vary depending on design decisions and the number of temperature zones. A temperature zone is a zone that can be set to a particular temperature. Aircraft have between two (single aisle) and five (large widebody) temperature zones. The cockpit and the cargo hold are fed separately. The ECS ducting requires substantial volume. As air inlets in the cabin are usually placed overhead the passengers, the air needs to be ducted into the upper part of the cabin. This requires so-called riser ducts, which may require the deletion of windows. Figure 1 shows the fresh air ducts of the A320. Note the arrangement with local riser ducts. [7] [6]

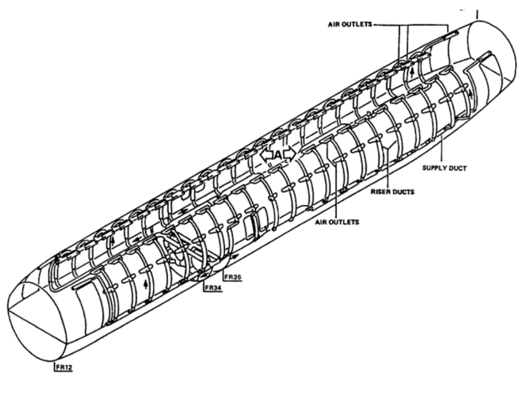

Figure 1: Fresh Air Ducting in the A320 (from [1])

2.3 Electrical Power System - EPS

The electrical power system (EPS) includes both the direct current (DC) and alternating current (AC) system. Electrical power is required in almost every part of the aircraft, and hence the system is of considerable complexity. For this work only a limited number of components is considered. Current EPS use so called power centers to distribute the electrical power received from the generators. These power centers distribute the power to all consumers inside the fuselage. Large consumers of electrical power usually use AC power, but many small consumers inside the cabin require DC power. Electrical components also produce excess heat. Traditionally the power center is placed in the forward part of the aircraft, in the room below the cockpit and in front of the forward cargo hold. New EPS concepts ("More Electric Architecture" - MOA) require a substantially more powerful electrical system and hence larger and heavier power center. The B787 - which uses electrical power instead of bleed air for its ECS - has two power centers, of which one is located behind the landing gear bay. [6] [3]

2.4 Water & Waste System - WWS

The Water & Waste System (WWS) is required for the galleys and lavatories. While small commercial and business aircraft sometimes omit such a system, commercial aircraft with 100 and more seats require them. The source of the fresh water is the fresh water tank, which is always located inside the pressurized fuselage. From the fresh water tank galleys and lavatories are supplied. The pipes are relatively small in diameter. The waste water is ducted back to the waste water tank. As underpressure is used to suck the waste water into the waste tank, the ducting for the waste water is more constrained. The exact position of the galleys and lavatories depends on the particular cabin layout, while their position is constrained to zones inside the cabin. [8]

2.5 Other Systems

The systems that are not considered include the hydraulics, the fuel system, the bleed air system, flight controls and communication and entertainment systems. The bleed air system connects the engines with the auxiliary power unit and is limited to a single duct inside the fuselage. Hydraulics run through the fuselage to supply the nose gear, the cargo doors and the empenage control systems. The hydraulic components are limited to pipes with small diameter. Most major components of the hydraulic system are placed inside the landing gear bay. The fuel system is like the bleed air system limited to a connection between the wings and the empenage, where the APU requires fuel or additional fuel tanks are located. Flight controls include cables in case of conventional aircraft and wires in case of fly-by-wire aircraft. Modern aircraft omit any cable-based flight controls, so that flight controls inside the fuselage are limited to wires transmitting low energy binary or analogue information ([2]). Communication and entertainment systems add considerable amount of wires as sources and sinks are widely distributed over the cabin and fuselage. The fact that low-energy analogue or digital information is transmitted allows a flexible routing. Often several types of wires are concentrated in so-called racetracks.

3 Tool Description

3.1 Fuselage Modeling

The positioning of system components depends on the geometrical characteristics of the fuselage. That is, component location and routing adapt to the specific geometry of a particular fuselage. Therefore a detailed knowledge of the fuselage and all its components is necessary. This includes the cabin with the monuments and overhead stowage bins. Further structural features such as doors, vertical struts, wing box and landing gear bay. Many systems are located below the main deck in the unused volume between the skin and the cargo hold. Therefore the cargo hold needs to be defined.

The basis for the fuselage model can vary. One option is the usage of a CPACS-inputfile defining an aircraft configuration (see [5]). CPACS provides sufficient information for the arrangement of the fuselage. The usage of a CPACS interface allows the interaction with other tools in the aircraft design process.

For that purpose a fuselage layout tool is used, which is also used for other applications (see [12] and [11]). The tool generates a detailed three-dimensional model of the fuselage and the cabin. The model is used to generate a geometry for the system layout. When looking at the cross section, the areas left and and right of the vertical struts (so called triangle area) are available for systems. Further the area below the cargo floor and the area above the cabin (crown area). The main deck floor beams are used for many cables and wires, but are unable to accommodate anything larger. For the path finding the unused areas are mapped at each frame position. Figure 2 shows a typical cross section of a single aisle. Larger cross sections usually offer more surplus space.

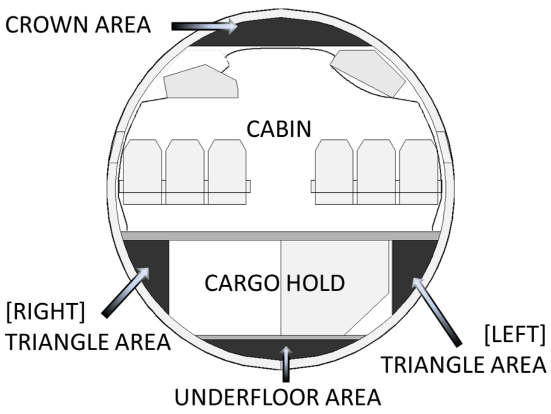

Figure 2: Single Aisle Cross Section

3.2 Placement of Large Components

Large components such as the mixer unit, the water and waste tanks and the power center have a limited number of possible locations. The mixer unit for example can be located in front of the wing box, but also behind the main landing gear bay. Using design rules derived from current technology aircraft the components are sized and adapted to the local constraints. The placement therefore represents an application of knowledge-based engineering. The consideration of different locations for a component (for example the fresh water tank) is cumbersome as geometric constraints are different each time. These need to be coded and tested. Figure 3 shows a possible location of the waste water tanks. They are located in the rear part of the fuselage, beneath the main deck and between the rear end of the cargo hold and the pressure bulkhead. Tanks are constrained by the structural layout. Such knowledge patterns need to be identified from current aircraft, and integrated into the tool. Although cumbersome, no real alternative exists.

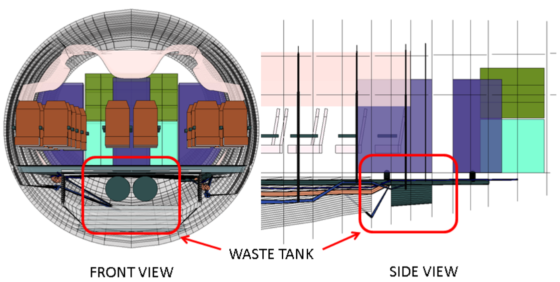

Figure 3: Location of waste water tanks in rear fuselage.

3.3 Path Finding Algorithm for System Connections

When major components are placed the system connections are created. Connections are defined by a start and an end coordinate. The path finding algorithm finds a route in the selected area (triangle, crown, underfloor) and blocks the required volume at each frame location. The areas are separated into squares of 2.54cm length (one inch).

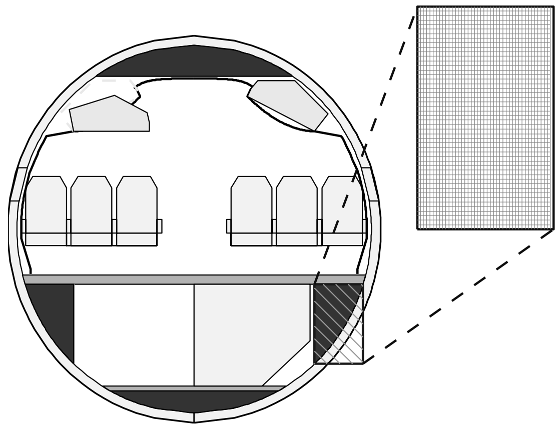

Figure 4: Discretization of triangle area for path finding

The algorithm uses a mapped field of the respective area. Each field in the 2D-matrix represents an area, which is either blocked or free. Figure 4 gives an approximate impression how this mapping works. The algorithm searches - depending on settings from bottom to top or vice-versa - the field for a spot sufficiently large to place the duct. The used nodes are then blocked for follow-up searches. The minimum area any duct or wire can occupy is a single node, hence the node length is of importance. An important limitation is that all ducts occupy a square field, although the majority are actually of circular profile.

In case of the ECS the mixer unit needs to be connected to the individual air outlets in the cabin. Each temperature zone is connected to the mixer unit via an individual duct. Often the ducts are separated into left and right side. The air outlets are all above the the seats, so that the air needs to ducted upwards. The cabin sidewall leaves only limited room. The problem is solved either by a number of individual riser ducts (A320 family) or by a single large riser duct (B737). The latter has the disadvantage that a window needs to be deleted. In figure 5 the ECS and WWS ducting in a single aisle cross section is depicted. Note the riser ducts at every second frame.
ECS ducts are also sized in diameter in dependence of the air flow required. Maximum allowable flow velocities can be defined for different types of ducts.

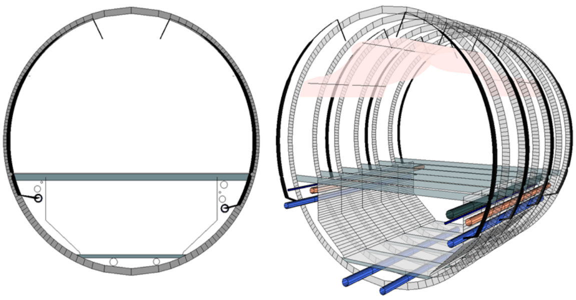

Figure 5: ECS and WWS ducting in a single aisle cross section

4 Examples

Today's aircraft share many characteristics when it comes to system layout. This is in part due to the very similar configuration of current aircraft, which share a low-wing design with wing-mounted engines. However, some system components are placed in different regions and in future changes in configuration or different system technology may change the state-of-the-art in system positioning.

4.1 Placement of Mixer Unit

The mixer unit is a central element of the ECS. It receives the pre-conditioned air from the packs and mixes it with re-circulated air from the cabin. The air is then transferred via pipes to the different temperature zones. A current generation single aisle aircraft usually features two temperature zones, a separate supply for the flight deck, and air supply for forward and rear cargo hold. The mixer unit is normally placed in front of the center wing box. This position is close to the air conditioning packs, which are usually located close to the center wing box, but outside the pressurized fuselage. If for example a rear engine configuration is sought, or the location of the packs is less constraints due to MOA, the mixer unit could be placed anywhere. However, with changing location the length and routing of the ECS ducts changes. In general the configuration with shortest ducting is best. But other advantages may compensate for slightly increased pipe length. Additionally, although the ECS ducts are of considerable volume, their specific weight is low.
In figure 6 to 9 three configurations are shown. The standard layout for current aircraft is a mixer unit in front of the wing box. Alternative layouts could see the mixer unit move behind the main landing gear bay or just in front of the aft bulkhead. Reasons could be a different pack location or engines placed at the rear end of the fuselage. Note that all shown examples have two temperature zones supplied via a single riser duct directly at the mixer unit. This layout is comparable to that of the Boeing single aisles (B737, B757). Further ducts for the cockpit, the avionics bay and the cargo holds are shown. Recirculation ducts transport the extracted cabin air back to the mixer unit.

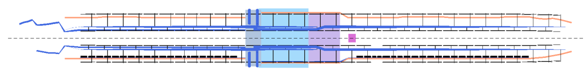

Figure 6: Mixer Unit in front of Center Wing Box, top view.

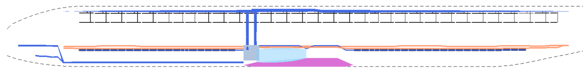

Figure 7: Mixer Unit in front of Center Wing Box, side view.

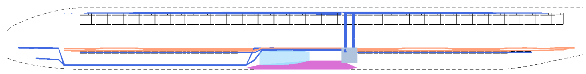

Figure 8: Mixer Unit behind of Main Landing Gear Bay, side view.

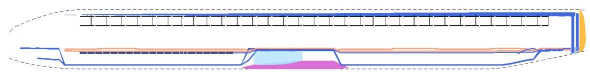

Figure 9: Mixer Unit in front of Aft Bulkhead, side view.

4.2 Temperature Zones and Riser Ducts

Aircraft have different temperature zones. These are zones in which a constant temperature is held. Reason is that different cabin sections require different level of cooling. Economy class cabins are populated, so that more cooling is required. If different classes share one temperature zone, the resulting level of ventilation might easily become uncomfortable for either of the class inhabitants. A common issue in ECS integration is the location of the riser ducts. That is, at which point shall the fresh air from the mixer unit be ducted into the crown area. Several solutions exist. The A320 uses riser ducts for each air outlet, which are small enough to be routed around the window. The B737 uses a single riser duct resulting in the deletion of a window. Widebodies use either a single riser duct for each temperature zone or a number of small riser ducts.

In figure 10 and 11 two different solutions are shown for a single aisle aircraft. The first figure shows a solution with local riser ducts. Although no window is lost the required volume in the triangle area is increased. The second shows a solution with central riser ducts for each of the three temperature zones. In this case the windows at that frame would probably be lost.

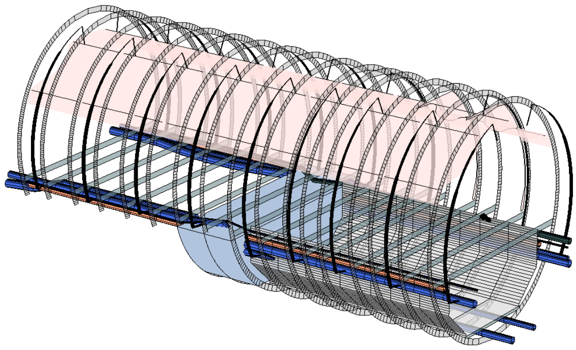

Figure 10: Center section of single aisle, ECS ducting for three temperature zones, local riser ducts

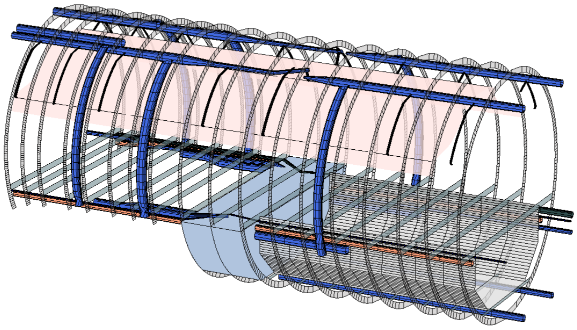

Figure 11: Center section of single aisle, ECS ducting for three temperature zones, central riser ducts

4.3 Power Center Location

"Power Center" is the common name of the centralized electrical power distribution. Rectifiers, inverters, batteries and other equipment for the AC and DC power generation are also placed here. Traditionally the power center is located close to the cockpit, also because the circuit breakers are located inside the cockpit. More Electric Architecture (MOA) results in generally more electrical power in the aircraft, in the region of 100kW and more. Such power requires a larger power center. Shifting the power center to the center of the fuselage, or splitting it into two separate centers are options. Volume constraints, heat development and maintenance requirements also add to the list of criteria. Different to the previous two examples, the shift of the power center has less visible results.

In figure 12 two different locations are shown. Shown on top is a power center located in front of the aircraft. Below is a power center located behind the landing gear bay. The power center is connected to local distribution centers that represent the electrical consumers in the cabin. The power center is connected to the generators and other power sources.

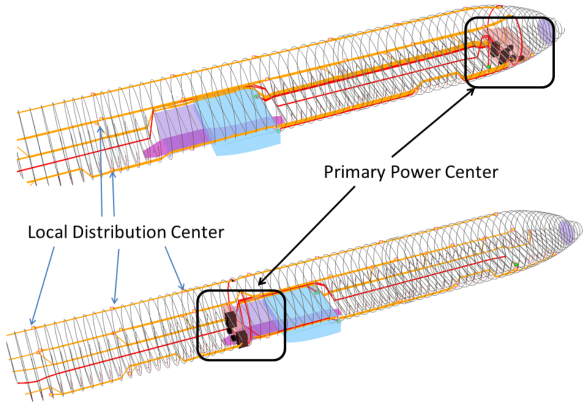

Figure 12: Location of power center and power wiring for two different power center locations. Note local distribution centers.

5 Overall System Layout

New aircraft configurations may require a change in general system architecture. This is due to changing position of power sources, for example if the engines are located at the rear fuselage. In order to keep power and bleed lines short or to optimize the utilization of fuselage volume for payload, some items may be located different than common on today's aircrafts.

In figure 13 a possible system layout is shown. Visible is the mixer unit in front of the center section, the power center below the flight deck and the waste tanks at the rear end of the pressurized fuselage. Inbetween are connections between the sinks and sources. The ECS ducting uses local riser ducts with feeding lines below the cabin surface. The shown layout is comparable to that of the A320.

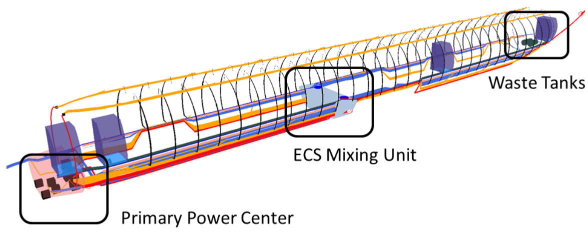

Figure 13: A320-like system layout with mixer unit placed in center section and forward power center.

In figure 14 an alternative architecture is shown. This architecture might be more suitable for aft mounted engines. The mixer unit is located behind the rear cargo hold, the power center is located behind the landing gear bay. The fresh water tanks are located in the forward part, the waste tanks in front of the center wing box. Different than the previous layout, the ECS ducting is changed with two main riser ducts supplying the two temperature zones. The ECS ducting for the cabin is mainly located in the crown area.

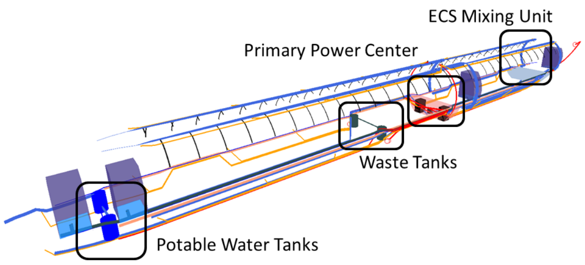

Figure 14: Alternative system layout with mixer unit placed in rear section and mid power center.

The objective of the presented method is to gain additional information in very early stages of the design. System weight is a quantity that can only be guessed in early stages. When the method is used a better understanding of actual system parameters can be obtained. In table 1 the length and surface of the previous two examples are given. In case of ducts the total surface is of primary interest as it correlates to the weight of the ducting. As can be seen from the table, the length is not necessarily a good indicator of the surface. The alternative ducting reduces the overall length but increases the overall surface, probably resulting in increased weight. Same applies for the water and waste system. Both the ECS and the WWS have limited pressure difference to the surrounding fuselage.

	Unit	A320	Alternative
ECS Duct Length	m	562	492
ECS Duct Surface	sqm	116	152
WWS Duct Length	m	693	622
WWS Duct Surface	sqm	140	175
Wire Length	m	1752	1334

Table 1: Resulting length and surface of wires and ducts shown in figure 13 and 14.

In table 2 the effect of different mixer unit position and riser duct concept is shown. "Local Riser Duct" describes the concept used in the A320 with ducts at every second frame. "Central Riser Duct" resembles the concept used in the B737 series with a larger duct. Many other considerations influence the choice of the ECS ducting layout, so the length and surface is only one criteria.

Mixer Unit	Riser Duct	Duct Length	Duct Surface
		m	sqm
Front	Local	562	116
Front	Central	378	101
Aft	Local	574	119
Aft	Central	390	105

Table 2: Resulting length and surface of ECS ducts for different layout concepts.

Cabins can be divided into different temperature zones. Generally, more zones allow a better adjustment of the temperature. However, any additional temperature zone increases the complexity of the ECS ducting and system layout. In table 3 the overall length and surface of the ECS ducting for one, two and three temperature zones is provided. It can be seen that the increases in duct surface is small and that the weight of the ducts is of reduced importance.

Temp Zones	Duct Length	Duct Surface
	m	sqm
1	367	104
2	397	109
3	411	111

Table 3: Effect of number of temperature zones on ECS ducting characteristics.

6 Summary and Conclusion

The presented paper introduced a method for system layout in preliminary aircraft design. The method allows a geometric analysis, but also allows to derive parameters for physical modeling. The routing is supported by a path finding algorithm. The locations of major components and chosen routes for connectors are based on knowledge of current aircraft.
The method may enable system layout studies at very early stages of the design. Further, new system technology like displacement ventilation, fuel cell integration and more electric architecture can be analyzed more effectively. This allows more integration in preliminary aircraft design.

Creation of a suitable system architecture is a very complex process. The presented method provides only a simplified architecture and is not suitable for detailed design. The required effort to close the gap to the usual CAD modeling is huge and probably uneconomical. The tool is ideally placed as support for system design.

Future developments may see a coupling to physical modeling tools, so that performance of the ECS or EPS can be estimated from the chosen layout. This may allow better weight and energy consumption estimations. The mentioned data exchange format CPACS represents a suitable platform for such coupling of analysis tools.

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