Architecture of air conditioning system with electric-motor-driven blowers

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Abstract. Architectures for air conditioning systems based on electrically driven air pumps for perspective commercial aircraft with a high level of electrification are very diverse. To select the optimal structure of such air conditioning systems for a specific aircraft and to create a scientific and technical groundwork for systems of this type for a wide class of commercial aviation aircraft this article proposes a combinatorial-logic method for design architecture of air conditioning system with electric blowers. The method is based on an oriented graph of combinations of subsystems and units with an assessment the quality of each variant in terms of aircraft fuel efficiency. The method allows to design a concept of on-board equipment in order to create an aircraft with a high level of electrification and to form a knowledge base on air conditioning systems with electric blowers, as well as a hybrid air conditioning systems where electric blowers are combined with other sources of fresh air to supply the aircraft’s pressurized cabin.

1. Introduction
The concept of future energy-efficient mainline aircraft address to convert most or all airborne aircraft systems to a single type of energy – electric energy (respectively, the concept of “more electrified aircraft” and the concept of “fully electrified aircraft”) [1]. One of the main requirements for air conditioning systems of such airplanes is the rejection of air bleeding for the needs of air conditioning systems from the compressor stage of a gas turbine of jet engine in favor of intake of external air through special air intakes and air compression using electric blowers [2]. The classical principle of air consumption from jet engine is associated with increased fuel consumption and significant loss of jet engine power. The lost power can reach 500-700 kW at a mainline aircraft. The electric air conditioning systems allows reducing the power taken from engines by two or more times [3]. However, even in this case, air conditioning systems remains the most energy-consumption constantly working on-board system, which largely determines the requirements for the power and architecture of the aircraft’s power supply system as a whole.

This is the basis for research the most energy-efficient architecture using the electrically driven principle of pressurization of a cabin in the process of forming the concept of the on-board systems of a certain aircraft, as well as for creating a scientific and technical advance of this class of air conditioning systems in order to be prepared for appearing a new more electrified aircraft generation. System designers can not choose the most efficient architecture with new technical solutions because they use mostly the base of past designing skills and they have a lack of information of innovations.

The system integrator of the on-board equipment of a promising aircraft, which does not have sufficient experience in integrating the on-board avionics with systems based on new principles, is in
In this regard, it becomes urgent to create an approach for the synthesis and analysis of air conditioning systems, as one of the main energy-consuming aircraft systems, which would allow us to consider the widest possible range of system designs with an analysis of their effectiveness. This paper proposes an approach, a combinatorial-logical method for making solutions of multivariate systems based on a directed graph [4] of practicable combinations of the solutions (alternative decision tree, or A-tree [5]) is proposed. Various expressions, as indicators of the effectiveness are used to assess the fuel efficiency of the aircraft [6, 7]. Further, an electric air conditioning system means a system with electric blowers which can be the only source of compressed air, or can work in combination with other sources of compressed external air (hybrid and combined systems).

2. Methods and materials

Air conditioning system with electric blowers for commercial aircraft in its most general form can be represented by a structure consisting of the following components (Figure 1): a subsystem supplying the outdoor air with the use of electric blowers, a subsystem of the primary air cooling; a subsystem of temperature and humidity of air control; a subsystem of the target temperature control of heat zones and compartments of the aircraft; an air distribution with the recirculation loop; a cabin pressure control system for automatic regulation of the pressure in the pressurized cabin. In addition, the air conditioning system provides the certain temperature mode of avionics and power electronics. The system also provides an aircraft of neutral gas and pressurization of hydraulic system [8]. There can be added another subsystems apart of the presented subsystems in Figure 1 such as liquid coolant and refrigerant coolant systems.

A preliminary review of possible solutions of electrical air conditioning systems or systems with auxiliary using of electric blowers demonstrates a lot of versions of the systems that require scientific and technical and economic analysis. Thus, in the thermodynamic circuits of the air preparation subsystems can present air cycle refrigerating machines with turbochargers of various designs, vapor compression machines of direct cooling/heating or using a secondary coolant, various combinations of air cycle refrigerating and vapor compression machines (combined systems) can be used. In such systems, air cycle refrigerating and vapor compression machines can work in series or in parallel. There are possible systems with air extraction from the fan circuit of the main engine of the aircraft, followed by increased pressure by the auxiliary electric blowers with low power (hybrid systems). Targeted air temperature control can be carried out by the classical method of mixing hot and cold air flows, electric heaters or heat exchangers, as well as combined systems. Hot compressed air is separated to two flows. One flow is a flow of circuit of itself hot air and another is used for preparation of cold air circuit. Figure 1 shows some possible versions of the subsystems that make up the air conditioning system. Various combinations of these subsystems give different circuits and constructive solutions of air conditioning system. These solutions have different weights, volumes, technical complexity, level of energy consumption and the degree of influence on the design of the aircraft and associated on-board systems. These parameters determine the efficiency and technical level of each individual solution. In addition to the shown usual components in circuit solutions there have to be presented innovative developments, which are represented at numerous patents in the field of air conditioning systems.

In the conditions of such a constructive variety, it is very difficult to find the most rational circuit solution for a particular system. It is even more difficult to create a database of rational solutions of such systems for different types of aircraft. The creation of such a database requires the analysis of a very large number of circuit solutions. A designer is not able to analyze it using only own experience. In this case, there is a high probability of loss of non-obvious, but effective technical solutions. An effective tool for structural, parametric synthesis and design of multivariate technical systems, such as, for example, the considered air conditioning systems that is consisted of functionally related objects, is the combinatorial-logical method of directed graphs [4], or “Alternative-trees” [5]. The variety of options for the implementation of the electric air-conditioning systems that is demonstrated above can be visualized in the form of the oriented graph. The graph is shown in figures 2-4.
Figure 1. Structure of electric air conditioning system and its subsystems.

The graph is constructed in the form of a “collapsed” alternative-tree, where all decision graphs (air conditioning systems structures) are reduced to one common final vertex - “Performance Indicator”. Each vertex has associated vertices of the next functional level (sub-vertices or descendants). The vertices (sub-vertices) of the graph have names of functional modules and subsystems of air conditioning
system. The names of the vertices indicate their circuit designation. The composition of the alternative-tree (names of vertices, directions and edges) can be considered as a prototype for the classification of air conditioning systems using an electric compressor in the cabin pressurization system. However, the presented alternative-tree is not limited to this.

In general, the directed graph includes many minimally functionally complete circuitry solutions that are formed from a combination of functionally and technically compatible, technologically feasible components. The alternative-tree of such circuitry solutions is called basic.

The connected components of this set built sequentially into the technological chain implement the process of targeted change of air parameters in the climate control system of the pressurized airplane cabin and the operation of heat-dependent on-board equipment. From a technical point of view, this chain starts from outdoor air intake devices, passes through the functional edges of any one of the possible circuit structures of air conditioning systems, and ends with devices for removing air from the pressurized cabin. This determines a specific technical solution – a decisive graph of a generalized alternative-tree. The final peak – “Performance Indicator” gives a technical and economic assessment of the solution. As such an assessment, the fuel efficiency of the aircraft is used [7], or rather, its change in the implementation of the selected version of air conditioning systems, or other integral indicators of aircraft perfection.

The basic alternative-tree can be considered as a tool for the formation and evaluation of the effectiveness of possible looks of the new generation of air conditioning systems. For this, it must have sufficient “power” so that the search for combinations of functionally connected components of air conditioning system is effective, i.e. the search should give distinct, workable holistic circuitry options that match the specified design parameters in the design operating conditions, i.e. the search should give distinct, workable holistic circuitry options that match the specified design parameters in the design operating conditions. Components included in the base alternative-tree are themselves generalized structures of subsystems with an increased level of detail. Based on such a developed base alternative-tree, a sequential structural, parametric and structural synthesis of the system and analysis of the obtained solution according to the indicated objective indicators can be performed.

3. Results and discussion

In terms of set theory [9], the base alternative-tree is represented by the vector \( (G, S, y) \), where:

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G = G (X, D)
\]

is the root (in this paper, the base) oriented tree with many vertices \( X = \{x_i\} \) and sub-vertices (descendants) \( \{x_{ik}\} \) (in Figures 2, 3, 4 the vertices and sub-vertices are indicated by named cells, which mean the corresponding components of air conditioning system, or the logical values “yes”, “no” regarding the use of some technical/physical principle); \( D = \{d_j\} \) is the set of edges (directed numbered or marked arrows); \( S = \{S_k\} \) is the set of edges emerging from one vertex.

The maps \( y(s) \) establish a logical relationship (logical operations) between the components of air conditioning system connected by the edges and indicated by the signs of the logical relation: \( \lor \) – disjunction (“OR”), \( \not\lor \) – "exclusive OR" (“XOR”), \( \land \) – conjunction (“AND”), etc. The output parameters of the vertices are the input parameters of the vertices of the lower level. Formally, the parameters are passed through the edges \( D = \{d_j\} \).

The initial conditions (the parametric part of the design task on the air conditioning system) are laid at the root vertex. The initial conditions include the typical requirements of the technical specifications for the air conditioning systems of the certain type of aircraft. The functions of the vertices \( X = \{x_i\} \) and the vertices \( \{x_{ik}\} \) are expressed by the operators \( A_i = \{A_{ij}\} \) and \( A_{ik} = \{A_{ijk}\} \), where \( i \) – the serial number of the vertex, which in our case is replaced by an identifier – the name of the vertex function; \( j \) and \( k \) are, respectively, identifiers denoting the \( j \)-th function in the sub-vertex \( k \) of vertex \( i \). The operators \( A_i \) and \( A_{ik} \) are, in most cases, algebraic relations that reflect the thermodynamic, mechanical, and other processes in their static model (calculated operating modes) that occur within this vertex/sub-vertex – a component of air conditioning system based on the parameters transmitted from the connected vertex/sub-vertex (flow rate, temperature, pressure, humidity or enthalpy of air, or liquid coolant (LC) parameters, as well as the total mass of the previous components in the circuit).
Figure 2. Upper part of alternative-tree.
Figure 3. Middle part of alternative-tree.
Heat Exchange System
- Freon-to-Air Heat Exchangers
- Air-to-Liquid Heat Exchangers
- Electrical Heating

Air Mixing System
- Electricity System
- Pressurized Cabin
- Cabin Pressure Control System
- Aircraft Target Temperature Control System
- Hot and Cold Air Mixing System
- Recirculation Air Subsystem
- Preparation of Air for the Cockpit Subsystem
- Power Electronics and Onboard Refrigerators

Figure 4. Bottom part of alternative-tree.
The operators $A_i$ and $A_{ik}$ calculate the components of the performance indicator of air conditioning system, which is the mass of the structure that implements the functions of this vertex, or other additive technical and economic indicators. As the decision graph is formed, the components of these indicators are transmitted through the edges $D = \{d_j\}$ of the decision graph of the alternative-tree and accumulate during their growth. The end nodes “Performance Index” on the base alternative-tree are combined into one component, where, $g_n$ value of mass of air conditioning system which calculates the increment of the take-off mass of the aircraft $\Delta g_{ac}$. The value of mass is based on the accumulated for each $\mathbf{n}$-th solution ($\mathbf{n} = 1...N$, where $N$ is the total number of productive decisions of air conditioning system under given initial conditions). The mass $\Delta g_{ac}$ takes into account the effect on changes the weight of associated aircraft systems and the required amount of fuel. The complete enumeration of all $N$ solutions gives a pair $R = \{G_n, r_n\}$, where $r_n$ contains a sequential list of edge numbers $r_n = \{d_{jn}\}$, which forms the $\mathbf{n}$-th decisive graph. Priority solutions on the value of $\Delta g_{ac}$ are determined during the process of analyzing the vector $R$. The solutions can be restored, detailed and developed to the required design level using the list of edges $r_n$. Since the values of $g_n$ are an additive quantity from the indices $g_{jn}$, $g_n = \Sigma g_{jn}$, which depend on the methods of thermodynamic conversion of air flow, secondary heat carrier, or energy conversion in the components of the air conditioning systems circuit (vertices of decision graphs), we can use as the initial base alternative-tree as a basic graph whose operators $A_i$ and $A_{ik}$ be only the weight or mass-dimensional functions of the corresponding technical devices. In this interpretation of the base alternative-tree, it is advisable to operate with the mass-dimensional parameters of the components related to the reference values corresponding to any electrified air conditioning system of an aircraft of a similar type, for example, the air conditioning system of long-range aircraft Boeing-787 [10].

The installation weights of most typical units of air conditioning systems are known from sources as [7] or are established on the basis of modern developments. They are statistical functions of changes in the state of the working fluid or energy conversion in the unit (the ratio of the characteristic parameters of the unit at the input and output). These changes are necessary and, in our case, sufficient characteristics of the unit to determine the mass of unit. The mass formulas of atypical devices included in the base alternative-tree (patent components) characteristic of inventive products are to be determined. The last can be based on the analysis of analogues in the aircraft design or general industrial area. This is one of the most time-consuming and controversial tasks of forming a basic alternative-tree, since patent descriptions in many cases are limited only to explaining the principle of the invention.

In a more developed structure of the alternative-tree, the operators $A_i$ and $A_{ik}$ can be finite-state machines, transfer functions, matrix operations, and, ultimately, CAD components (fragments of the thermal engineering scheme) with interfaces to the CAD components of the next vertex.

The solution to the synthesis problem from the basic alternative-tree consists in performing the natural steps of constructing complete chains of related components (decision graphs), starting with the selection of the edge coming from the root vertex and the sequential passage of variants of its descendants to the end vertex of each option with the final calculation of the efficiency indicator obtained decision graph.

Moreover, depending on the functional content of the vertices of the base alternative-tree, structural synthesis can be performed simultaneously, i.e. the formation of specific and isolated circuitry looks, parametric synthesis of the formed structure and, ideally, the structural synthesis of the system.

The structural synthesis applications based on non-planar graphs can help in the formation of the base alternative-tree. However, the specifics of the base Alternative-tree with operator filling of vertices makes it advisable to use special programming of combinatorial-logical enumeration of solutions. After the formation of a graphical representation of the alternative-tree and its operator filling, programming enumeration of solutions is not a significant difficulty. The dimension of the searching problem increases exponentially with increasing number of edges in the alternative tree and can become unreasonably large. This requires a rational organization of the process and filtering of productive solutions. A natural limitation of searching is the output of the calculated parameters at any vertex beyond physically or technically feasible limits, including those associated with the high-speed range of...
operation of air conditioning system. The calculated parameters need to be introduced at the stage of operator filling of vertices. The second limitation is the reduction of the functional chain of vertices, after which the remainder of the tree is the same for the solutions found earlier. A preliminary assessment shows that productive solutions for a certain alternative tree, passing through similar filters and restrictions, lie within a few hundred searches.

4. Conclusion
An approach is proposed based on the combinatorial-logical apparatus of oriented graphs (alternative-trees) for circuitry, parametric synthesis and synthesis of the designs of the electrical air conditioning systems at the stage of conceptual design of the aircraft and its on-board systems.

The practical goal of creating this method is based on the need to form a scientific and technical reserve in the field of air conditioning systems using electric blowers for promising aircraft with a high level of electrification and to ensure the synthesis of rational architectures of air conditioning systems for specific projects of new aircrafts.

The developed tool will be useful not only to the developers of air conditioning systems, but also to the system integrator of the on-board equipment set.

It is advisable for the system integrator to have a complete set of alternative-trees of all aircraft systems.

Moreover, a number of these tools should have the property of mutual influence, similar to the interconnections of the onboard systems themselves, for example: air conditioning system and power supply systems, air conditioning system and air signal systems, air conditioning system and aircraft digital computer system, etc.

Such mutual influence can be realized through the connection of the root vertices of alternative-trees and “cross-pollination” at the level of the sub-nodes with interdependent parameters.

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