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A Systematic Methodology for Populating the Aircraft Thermal Management System Architecture Space

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The aircraft thermal management system functions to provide suitable working conditions for pilot, crew, passengers, and the other aircraft systems. The additional weight, drag and power consumption caused by it greatly influences the performance of the aircraft. However, due to rising heat load of emerging novel aircraft concepts, traditional design approaches which rely on data and empirical equations may not apply to the future thermal management systems. Many existing literature which tried to identify the optimal thermal management system architectures only considered limited architecture space where the candidates were pre-selected in terms of experience or intuition. Therefore, viable but non-intuitive architectures may not be included in the design space. To fill this gap, this paper proposes a behavior-based backtracking methodology to systematically populate the architecture space by enumerating both intuitive and non-intuitive architectures. Thermal management requirements for traditional and novel configurations are used to generate the architectures. By comparing the generated architectures with existing ones, this paper validates that the proposed methodology is capable of generating both intuitive and non-intuitive architectures.

I. Introduction

Aircraft thermal management system (TMS) is an aircraft system to handle the cooling and heating requirements of the whole aircraft to keep the temperature of each aircraft system within an acceptable range during the operation. More specifically, the TMS functions to provide comfortable conditions for pilots, crew, and passengers, as well as providing suitable conditions for systems including the avionic, fuel, hydraulic systems, etc. [1] A conventional aircraft TMS is generally comprised of a fuel thermal management system (FTMS), an environmental control system (ECS) for the cabin, and some systems directly cooled by ram air [2]. The FTMS uses the fuel to cool the hydraulic systems and engine oil, but the heated fuel in the FTMS will also be cooled by ram air. The ECS is usually applied to supply cold air to cool the cabin and the avionics. The supply air is sourced from either the high pressure compressor (HPC) stage of the engine or electrical compressors. Before supplying to the cabin, the supply air is cooled by ram air through a air cycle machine (ACM). It should be noted that the largest amount of heat during operation is generated in the jet engines or combustion engines. However, in such conventional propulsion systems, most of the generated heat is rejected through the exhaust, thus there is no need for specific TMS to manage the heat generated inside the engine. The turbines may require cooling, but it is not the type of TMS to be architected in this paper. Therefore, the cooling systems inside the combustion engines or jet engines are not considered in this paper.

The design of TMS is important for the aircraft. On the one hand, the TMS is essential to ensure suitable operation environment for subsystems and the vehicle. Failing to meet the cooling or heat requirements might lead to performance degradation or failure of systems, or extreme discomfort of passengers and crews. On the other hand, the TMS can greatly influence the aircraft performance by adding additional weight and ram drag, as well as consuming power and extracting the bleed air. For example, the ECS, which is part of the aircraft TMS, is the largest consumer of non-propulsive power [3]. It was also shown that the ECS can account for 64.6% of the engine power at cruise condition on a military transport plane such as C-17 [4]. Therefore, the TMS has to be considered at early design phase to ensure correct functioning of the whole aircraft as well as to improve the aircraft fuel economy.

Traditionally, the TMS is viewed as a system of interactions that arise from emergent properties, that is, the TMS are constructed after the energy dissipation in the aircraft systems is determined [1, 2]. Therefore, the TMS may not be envisaged in the initial design [1, 2]. This architecting method can guarantee that the temperature requirements of each

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system are satisfied. However, such method may lead to suboptimal TMS architectures, which is constrained by the developed other subsystems. Meanwhile, this traditional architecting method does not provide any information regarding the properties of TMS themselves at the conceptual design phase. The properties, or the influences on vehicle design, of the TMS, are predicted using empirical equations that are derived from historical data, which can be found in aircraft design manuals [5]. However, the cooling loads in the commercial aircraft are greatly increasing due to expanded functionality and higher power demand of electronics [6–9], rising trend to electrify subsystems [10–13], and more application of composite material which reduces the amount of heat that can be convected to the environment [6–9]. Moreover, many novel commercial aircraft concepts that generate much larger amount of heat are emerging. There are three major types of the new concepts that present challenges to the empirical design methods: 1. More-Electric Aircraft (MEA) or All-Electric Aircraft (AEA); 2. Turbo-Electric Distributed Propulsion (TeDP) System; 3. Supersonic Business Jet (SSBJ). MEA [13] or AEA [11, 12, 14] is the concept to improve the aircraft fuel economy by electrifying subsystems. The increased heat is generated from the added electric components and the corresponded buses and control panels. TeDP system utilizes gas-turbine-driven generators to power motor-driven fans which are distributed along the wing [15, 16]. The major heat source is the propulsive electric motors. Such heat load is significantly larger than the usual cooling requirement in a conventional aircraft. For example, the heat generation for a 78-pax TeDP aircraft (20 MW propulsive power) is at the level of 880 kW as shown by the University Leadership Initiative (ULI) program [17], while the common ECS load is only around 160 kW for a conventional 350-pax aircraft. SSBJ is a class of business jets that performs civil supersonic transportation. The heating problem is primarily caused by kinetic heating and the increase use of composite materials. For these novel concepts, the thermal management requirements are quite different from the conventional ones, leading to a lack of historical data. Therefore, the existing statistical data and corresponded empirical design methodologies may not apply to the development of TMS in the future. New challenges for the development of TMS in commercial aircraft are rising.

There have been many research conducted on these novel concepts, and the corresponding TMS were also studied. However, many analyses of the TMS were only based on simple assumptions of technologies instead of using models with an actual TMS architecture. For example, Felder [15, 18] studied the TeDP concept and showed its advantages, where TMS options were assumed to be cryocooler or liquid hydrogen cooling. However, the performance of the TMS and its influences on the aircraft were only estimated based on parameters such as efficiency and specific power which were derived from expected technologies, without modeling the actual TMS architecture. Liu [19] performed a thermal cycle analysis of the TeDP system and presented a TSFC benefit, but the modeling of the TMS architecture was also neglected. Similarly, Welstead [20] researched a turboelectric concept, but only the weight of the TMS was approximated based on the specific power from a MEA configuration, neglecting performances and other influences of the TMS on the aircraft such as the power consumption. For research on SSBJ designs, as reviewed by Sun [21], many studies only focused on the reduction of sonic boom while neglecting the heating problem, or they made assumptions for the TMS based on Concorde even its data may not apply to the future SSBJ. Therefore, such high-level studies cannot provide instructions on how to design the TMS architectures. The impacts of the TMS on the aircraft might not be captured sufficiently either due to oversimplification of the TMS analysis. To improve the fidelity of the TMS analysis, a physics-based model is needed, which requires the construction of the TMS architectures.

Many researchers have already realized that the conventional TMS design method which relies on historical data and empirical equations cannot effectively handle the rising challenges of the future TMS development. Thus a lot work has been done in identifying the optimal TMS architectures for given aircraft concepts or thermal management requirements. Some researchers studied different TMS architectures by investigating different types of heat sinks. Dooley [22] reviewed different types of heat sinks and the technologies or fundamental cooling cycles associated with them, but such analyses were at very high level, without providing any guidance for the structural architecture. Vredenborg [23] investigated the thermal management architectures for fuel cell systems on-board commercial aircraft. Three types of heat sinks and possible heat paths were discussed. Such research on heat sinks provide information about the capability of each type of heat sinks, but the guidance of architecting the heat paths in TMS is not presented. Some researchers generated TMS architecture candidates by varying heat paths or types of cooling devices of a basic refrigeration cycle. Chen [24] proposed a highly stable two-phase thermal management system architecture. Several alternative architectures were generated by varying flow paths and adding additional components to an basic two-phase pump cycle. Rheaume [25] did TMS analysis on TeDP aircraft where the ECS for pilot and passengers was not included. The architecture of interest was limited to a combination of oil loop and a coolant loop. Donovan [26] investigated adaptive power thermal management systems. The candidate architectures were The candidate architectures were TMS that utilized different pumping systems. Alyanak [27] architected FTMS where the candidate FTMS architectures were generated by varying the re-circulation paths. Park [28] studied the global TMS architecture for hybrid electric vehicles.

Three different global TMS heat paths were generated for the further analysis while leaving the local TMS pre-selected and fixed. Shi investigated the impacts of two types of ECS on the engine performance and the aircraft missions [29, 30]. One was the conventional pneumatic ECS which extracted the bleed from the engine as the supply air, while the other used the air compressed by an electric compressor. These studies were to demonstrate the electrification of the ECS, but the architecture of the two ECS were fixed while only changing the air source. Shi [31] also conducted a design analysis of a regional aircraft with TeDP system for the ULI program. The baseline TMS was a conventional cooling oil/ram air system, but the generated heat could not be fully rejected. Thus the authors studied the options to use additional oil or phase change material (PCM) to solve this heating problem. The corresponding system- and mission-level impacts are also included. These researchers indeed tried to explore the architecture space by constructing multiple architecture candidates, but the candidate architectures were always pre-selected which were limited by intuition and experience without a systematic architecting approach. Thus some of the viable but non-intuitive architectures may not be identified in the architecture space. To search for the optimal TMS architecture, the architecture space needs to be fully explored, where both intuitive and non-intuitive architectures should be evaluated and compared. Therefore, the TMS architecture candidates constructed by only intuition and experience may lead to suboptimal design space.

To fill this gap, this paper proposes a methodology to systematically and sufficiently populate the TMS architecture space, by enumerating both intuitive and non-intuitive architectures. Inspired by Systems Modeling Language (SysML) [32] in Model-based Systems Engineering (MBSE), the proposed methodology firstly constructs the TMS behavioral architectures in terms of the fundamental thermal cycles that are utilized in cooling or heating. Then the TMS structural architectures are created based on the established behavioral architectures. The behavioral architecture refers to the architecture that describes how the TMS functions to cool or heat. The structural architecture refers to the architecture that describes what components are selected to perform the established behaviors, and how components are linked together. The enumeration is realized by a backtracking algorithm [33]. Therefore, it is a behavior-based backtracking approach. The TMS architectures generated using traditional thermal management requirements will be compared to the traditional TMS to validate that the proposed methodology is able to cover the conventional architecting need. By such comparison, it also validates that the proposed methodology can create non-intuitive architectures that are different from the conventional ones but are also physically valid. Similarly, TMS requirements a novel aircraft concept are also used to populate the corresponding architecture space to show the proposed methodology is able to generate both intuitive and non-intuitive TMS. Due to the space limit of this paper, the novel concept used to generate TMS architectures will be limited to TeDP configuration. It should be also noted that the proposed method of this paper is to populate both intuitive and non-intuitive TMS architectures, not guaranteeing the feasibility or optimality of the generated architectures. The optimal down-selection of the TMS architectures will be conducted in the future work.

The paper is organized as following: before introducing the proposed methodology, the scope of the methodology is discussed in Sec. II; the methodology is then presented in Sec. III; the cases to demonstrate the capability of the methodology are described in Sec. IV; then the results and validation of the methodology are shown in Sec. V; and the conclusions and future work are stated in Sec. VI.

II. Scope of the Methodology

In this section, the scope of the TMS that is focused by this paper is discussed. Aircraft TMS can be decomposed hierarchically into three levels as shown in Fig. 1: the global TMS, the local TMS, and the component TMS. The global TMS is comprised of all the local TMS, managing interactions between each local TMS and heat sinks. An example of the global TMS architecture is the TMS for conventional aircraft as shown in Fig. 2, which was constructed following the example shown in the book by Moir [2]. In this global TMS architecture, the interactions of each load are illustrated. The local TMS manages the heat within an aircraft subsystem to satisfy certain thermal requirements, where the components in this subsystem are rejecting heat (requiring cooling) to or acquiring heat (requiring heating) from the local TMS. An example of the local TMS architectures is a four-wheel condensing air cycle machine inside an ECS, which is used to cool the cabin. The corresponding architecture is presented in Fig. 3, which was developed by the author [29]. The component TMS cools or heats a component, by rejecting (requiring cooling) or acquiring (requiring heating) heat through a local TMS. Examples of the local TMS are cabin airflow circulation system [34] and electronics circuit cooling device [35].

This paper focuses on architecting the paths from the hot or cold source to the components that require heating or cooling, that is, to construct global and local TMS architectures while treating the component TMS with the cooling or heating load together as a component. To make it more clear, a cooling load is defined as a load that requires cooling, and a heating load is a load that requires heating. The component TMS is modeled with the component itself, considering the characteristics of heat generation and heat transfer to the local TMS. Therefore, the proposed architecting methodology focuses on populating the global and local TMS architectures. It should be noted that even though the architectures of the component TMS will not be constructed, different options of component TMS will be considered in the architecting process of the global and local TMS. For example, the component TMS that removes heat from an electric motor can use oil bath, water spray, PCM, or other alternative cooling approaches.

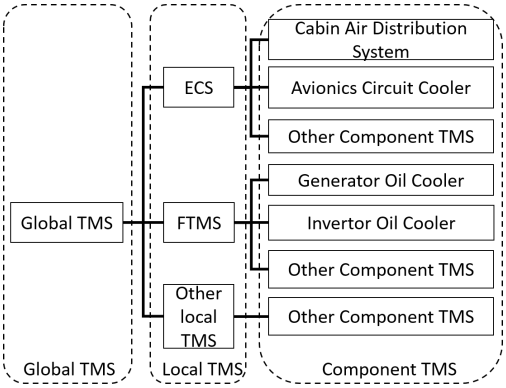

Fig. 1 Hierarchical decomposition of TMS

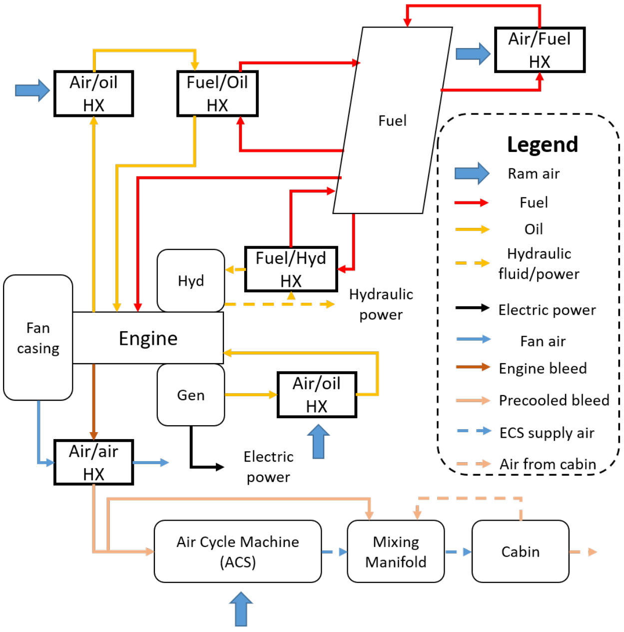

Fig. 2 Architecture of a conventional global TMS

III. Architecture Populating Methodology

A. Formulation of the Methodology

1. Information Needed for TMS Architecting

From research regarding TMS design and analysis at early design phase, it is discovered that the TMS architecting and analysis always start from the identification of the major heating and cooling loads in the aircraft. Staack [36] and Seki [37] discussed the necessity of application of a vapor cycle into a MEA ECS by firstly identifying the increased

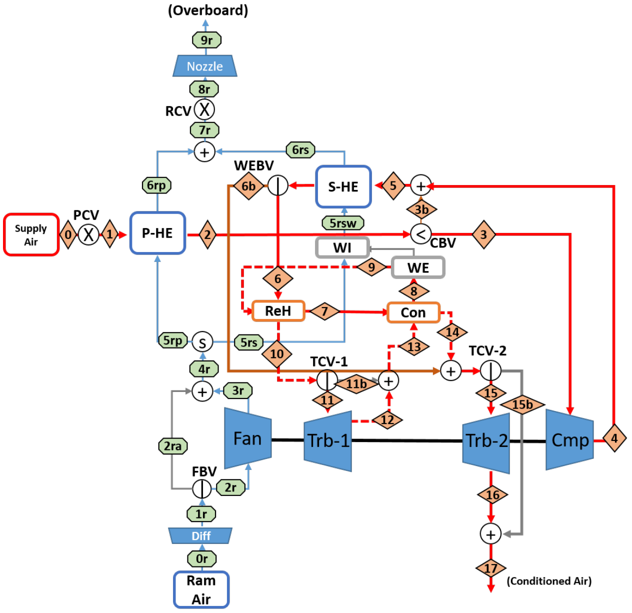

Fig. 3 Four-wheel condensing air cycle machine [29]

cooling load in the cabin. Petly [38] started the TMS research for a Mach 5 cruise aircraft with the understanding of the extreme kinetic heating problem. Donovan [26] began the research on a vehicle-level transient TMS modeling and simulation by defining the major heating sources in the aircraft of interest. Dooley [22] studied the TMS in terms of different types of heat sinks and Vredenborg [23] varied the TMS architectures in his work by using three different heat sinks. Most of the research regarding the TMS need to identify the major heating and cooling loads as well as heat sources and heat sinks, but due to space limitation only some typical studies are presented as examples here. Therefore, it can be concluded that a high-level description of the heating and cooling loads as well as heat sources and heat sinks is required for the TMS architecting.

2. Behavior-Based Architecting Approach

From the literature review, the TMS architectures are initially generated by guidance of rules or experience in existing solutions. However, too detailed rules or experience, such as "supersonic aircraft must use vapor cycle for air conditioning", or "hydraulic fluid should be cooled by fuel", can greatly limit the types of architecture candidates, leading to architectures only generated by intuition or experience. However, it is also observed that all the local TMS architectures either directly reject heat to the other media based on temperature gradient or follow the fundamental refrigeration cycle, which is stated by the second law of thermodynamics. The fundamental refrigeration cycle mentioned here refers to the cycle that requires energy to reject heat from a low temperature source to higher temperature medias. The alternative architectures are generated by varying components or heat paths. The varied components or heat paths are still served to the same cooling behavior for the fundamental cycle. For example, the compression behavior is required to lift the thermal state of the hot stream in the cooling cycle, and an expansion behavior is required to expand the hot stream for further cooling, and the compression behavior can be realized by turbine-driven compressors or electrical compressors, and the expansion process can be realized by turbine or expansion valve. From this example, it can be seen that even the types of component utilized in the thermal cycle are different, the same behavior is performed. Therefore, a hypothesis can be made for the guidance of generating local TMS architectures: all local TMS architectures manage the heat following the behaviors of fundamental physics (thermal cycles or behaviors of direct heat transfer based on temperature gradient).

The global TMS is defined as the system that arranges the interactions between each local TMS and heat sinks as in Sec. II. The arrangement are determined by the behaviors of local TMS in terms of the requirement for heat sinks and the type of cooling cycles. For example, if one of the local TMS requires ram air as heat sink and produces exhaust and another local TMS requires exhaust for cooling, these two TMS can be linked by routing the exhaust from the first local

TMS to the latter one. It should be noted here the "exhaust" from a TMS is defined as the media after it performs the heating or cooling function on a load. Another example is that if two local TMS require vapor cycle cooling, then these two TMS might be cooled by the same vapor cycle. Therefore, a hypothesis can be made for the guidance of global TMS architecting: all global TMS link their local TMS by following behaviors of each local TMS in terms of required heat sinks and applied thermal cycles.

Realizing all the TMS follow certain behaviors, the corresponding architectures then could be constructed based on these behaviors. Inspired by the System Modeling Language (SysML) [39] in Model-Based System Engineering (MBSE) [40], an architecture can be viewed as comprised of three parts: 1. behavior; 2. requirements; 3. structure. The part of behavior for TMS can be seen as the functions to be realized through the TMS, which can relate to the behaviors of fundamental physics. The requirements can refer to the heating or cooling loads that are managed by the TMS. The part of structure can be viewed as the final TMS architecture that gives the heat paths, heat sinks, and applied components. Thus, a behavior-based TMS architecting approach is proposed that a TMS behavioral architecture is firstly constructed by following the the behaviors of fundamental physics to satisfy the heating or cooling requirements, then the structural architecture can be created from the behavioral architecture. The linkages between the architecture description in SysML and the proposed architecting method are illustrated in Fig. 4.

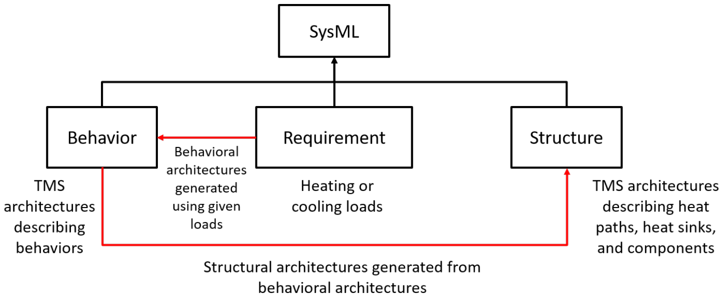

Fig. 4 Linkages between SysML and proposed architecting methodology

3. Backtracking Algorithm

To sufficiently populate the architecture space, a enumeration approach that is capable of trying every combination of behavioral options in terms of the compatibility is required. The backtracking method can fulfill such requirement. Backtracking is a general algorithm to find all solutions to problems, notably constraint satisfaction problems [33]. In the TMS behavioral architecting step, the compatibility of behaviors can be viewed as the constraints to be satisfied. The backtracking method is illustrated in Fig. 5. From the top level, it picks an option which is the node of the next level, and then picks an node that is compatible with previous nodes, and then move the next level in the same manner until a solution is complete. Then it backtracks to the parental node of the last node (assuming the last node is at level n, and the parental node is at level n-1), and picks another sub-node and proceed until another solution is complete. When the sub-nodes of the parental node at level n-1 are all explored, the process backtracks one level up of the parental node, which is at level n-2, and proceed with picking another node at level n-1. This process will continue until all the nodes are explored, indicating all the compatible architectures are solved. In the actual implementation, a compatibility function is used to identify the sub-nodes that are compatible to the current partial solution. A generic pseudocode for the backtracking algorithm using the compatibility function for this behavior-based architecting method is shown in 1. The compatibility for local behaviors will be discussed later in Sec. III.B, and that for global behaviors will be discussed in Sec. III.D.1.

4. Behavioral to Structural Architecture

With the constructed TMS behavioral architectures, the behaviors of each architecture can be determined, however, a structural architecture is also needed for the design and analysis during conceptual design phase. In the behavioral diagrams, each behavior can be realized by a set of candidate components. Therefore, the structure architecture space can be fully explored if all possible compatible combinations of the components for each behavior are enumerated. An illustration of the conversion from behavioral to structural architecture is shown in Fig. 6, where all components in this figure are assumed to be compatible.

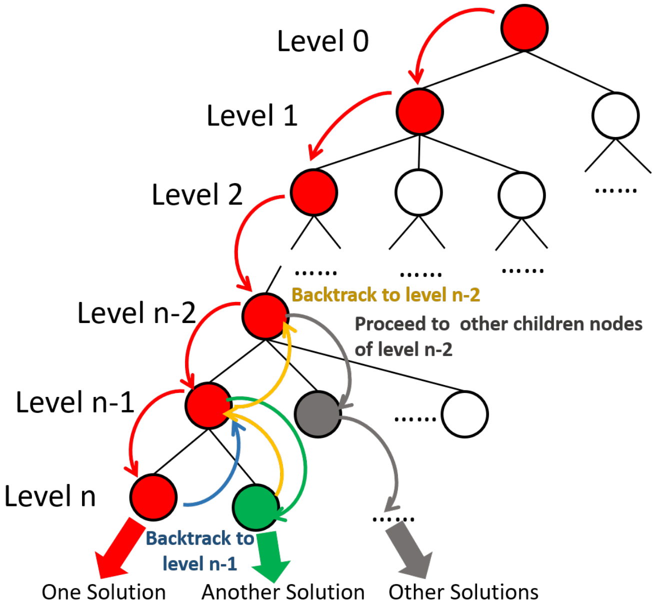

Fig. 5 Backtracking method illustration

Algorithm 1 Behavior-based backtracking TMS architecting

```
function FIND_SOLUTION($Load$)
    Initialize a list $Sol$ to store solutions
    find_sol_backtracking($Load$, $Sol$)
    return $Sol$


function FIND_SOL_BACKTRACKING($Load$, $Sol$)
    Select behaviors based on $Load$: $beh$
    if len($Sol$) > 0 then
        if $Sol[-1][-1]$ determines termination for current solution then
            $Sol$.append($Sol$[-1].copy())
            return
        else
            for $i$ in $beh$ do
                if $i$ is compatible with $Sol[-1]$ then
                    $Sol[-1]$.append($i$)
                    find_sol_backtracking($Load$, $Sol$)
                    $Sol[-1]$.pop()
    else
        $Sol$.append([])
        for $i$ in $beh$ do
            if $i$ is compatible with $Sol[-1]$ then
                $Sol[-1]$.append($i$)
                find_sol_backtracking($Load$, $Sol$)
                $Sol[-1]$.pop()
    $Sol$.pop()
```

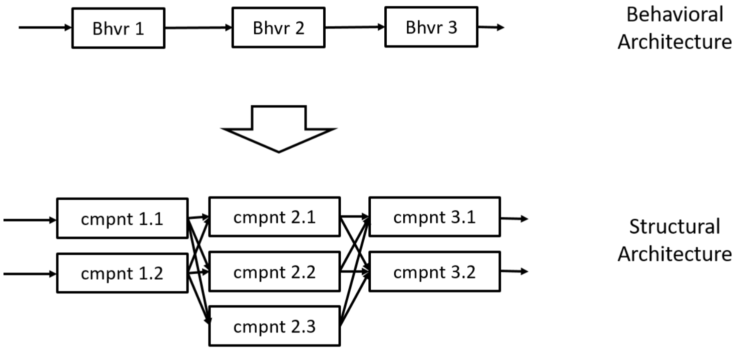

Fig. 6 Conversion from behavioral to structural architecture illustration

5. Overview of the Methodology

In summary, the proposed behavior-based backtracking methodology can be described as: the local TMS architecture space is populated firstly by backtracking based on behaviors of fundamental physics, then the global TMS architecture space is explored by enumeration of local TMS for each heating and cooling load and the interactions among these local TMS, following the behavior of the interactions of local TMS. There is also a need for conversion from the behavioral architecture to structural architecture, which is done by enumeration of components for each behavior. The overview of the architecting process is presented in Fig. 7.

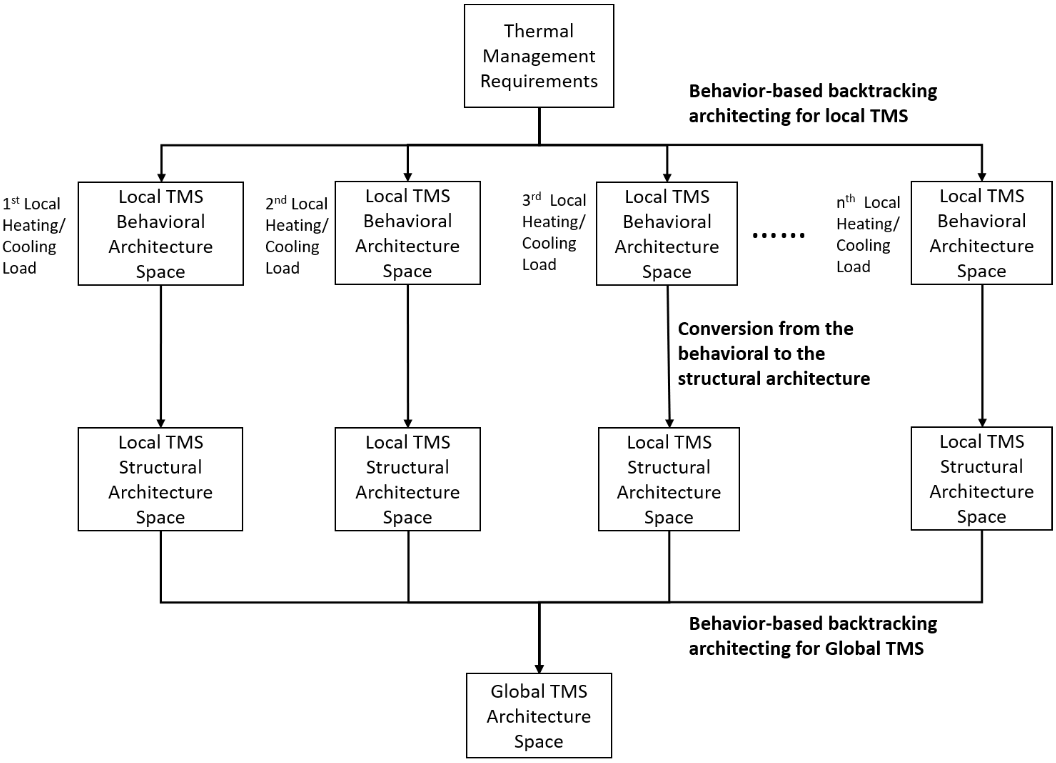

Fig. 7 Overview of TMS architecture space populating methodology

B. Local TMS Architecting

1. Behaviors of Local TMS

Compatibility is needed for the backtracking algorithm. The compatibility included in this section are mostly based on fundamental physics, although the compatibility of some behaviors are subject to user preferences such as the maximum number of compression or expansion processes. It should be noted that these compatibilities shown in this paper are only to demonstrate the capability of the method. Other specific constraints in terms of the actual application can also be added. A hierarchical diagram showing the behavioral compatibility for a load needing heating is illustrated in Fig. 8, and a hierarchical diagram showing the behavioral compatibility for a load needing cooling is illustrated in Fig. 9. In these two diagrams, the sub-nodes mean the only behaviors that are compatible with their parent node. Both heating and cooling load management will consider corresponded regulations to check if there are specific requirements to be obeyed. Such requirements might eliminate certain optional behaviors. For example, the regulation requires that the ECS should supply enough fresh air to the cabin while pressurizing it, which means that the ECS has to use the charged air (either from bleed or electrically compressed) as the heat sink. It should be also noted that the cooling nodes with "*" in Fig. 9 mean they are the same cooling behavior with the same sub-options. For example, if the "Cooling" node is reached under "Storage", then the next step will be to select "Direct heat reject" or "Refrigeration cycle".

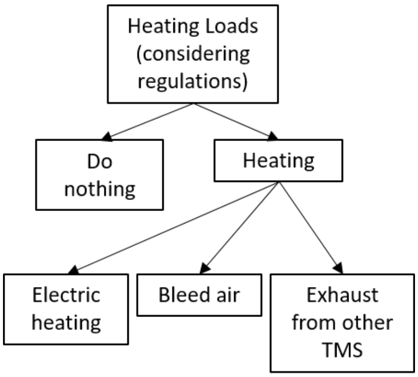

Fig. 8 Behaviors to manage loads requiring heating

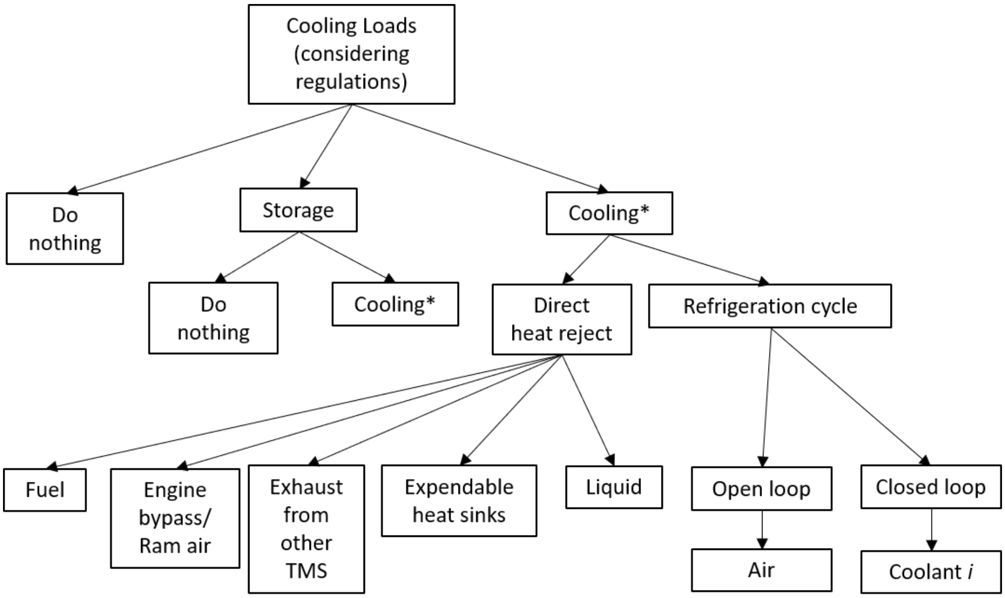

Fig. 9 Behaviors to manage loads requiring cooling

In Fig. 8, the node "Do nothing" means it does not take any other approach to treat this load. The sub-nodes under "Heating" are the selected options for heating a load: "Electric heating": apply electric heating panels; "Bleed air": use engine bleed air as heating source; "Exhaust from other TMS": use exhaust from other TMS as the heating source. In Fig. 9, "Do nothing" has the same meaning as in Fig. 8 that no specific actions will be taken to treat this load. "Storage" means to store the heat in certain energy storage materials such as phase change materials (PCM). As stated before, the "Cooling" option with "*" refers to the same node that has the same sub-nodes: "Direct heat reject" and "Refrigeration cycle", where "Direct heat reject" indicates cooling methods without using heat pump (without using external power) while "Refrigeration cycle" refers to cooling methods requiring heat pump. The sub-nodes of "Direct heat reject" are the potential heat sinks, and it should be also noted that oil is a sub-option included in "Liquid". For all "Direct heat reject" sub-options, the actual behaviors related to heat reject are: "Start", "Heat exchange (HX)", "Cooling the load (Load)", "End". Only for Fuel, there could be an additional "Re-circulation (Rec)" behavior. The detailed explanations and compatibility of the "Direct heat reject" behaviors are discussed in Table 1. For "Refrigeration cycle", there can be a open-loop option and a closed-loop option. Following these two sub-nodes, the corresponding heat sinks will be selected. For a open-loop option, only air is considered in this paper. For the closed-loop option, there can be a number of coolants and at the ith backtracking recursion, it will pick coolant i for further expansion to an actual solution. For this paper, three types of coolants are selected. The corresponding behaviors for "Refrigeration cycle" are: "Start", "Heat exchange (HX)", "Cooling the load (Load)", "Compression (CMP)", "Expansion (EXP)", "Water Extraction (WE)" "Re-circulation (Rec)", "End". The corresponding explanations and compatibility are discussed in Table 2. It should be also noted that for each load, there could be multiple cooling approaches working simultaneously to remove the heat, that is, multiple TMS can work parallelly for a single load. For example, an electric motor can both reject heat to oil and energy storage material at the same time. For this paper, it is allowed at most two TMS working on the same load to limit the number of generated architectures. It should be also noted here that these listed compatibility mostly follow the fundamental physics, and are only to demonstrate the capability of the method. They are subject to change in terms of the real applications.

Table 1 Behaviors of direct heat reject systems

Behavior	Explanation	Compatible if all conditions are satisfied
Start	Starting point in the architecture	No Start exists in the partial solution;
Load	Load is cooled	Start exists in the partial solution; Load does not exist in the partial solution;
HX	Heat exchanging with another heat sink, treating the current architecture as a load to be cooled	Start exists in the partial solution; Total number of HX in partial solution < k (k is a user specified number, 1 for this study); Current architecture is closed-loop; Load in partial solution;
Rec	Re-circulates back to the reservoir for closed-loop architecture	Start exists in the partial solution; Load exists in the partial solution; Current architecture is closed-loop;
End	End of the partial solution, termination condition for a solution in backtracking	Start exists in the partial solution Load exists in the partial solution Rec exists in the partial solution if closed-loop

When the backtracking step reaches the bottom level in Fig. 9, the behaviors stated in Table 1 and Table 2 are then used to construct the actual TMS behavioral architectures. When the behavior HX is encountered, it is treated as another load to be cooled, which starts from the top level of the backtracking tree as illustrated by Fig. 9. Therefore, a cooling

Table 2 Behaviors of refrigeration cycle systems

Behavior	Explanation	Compatible if all conditions are satisfied
Start	Starting point in the architecture	No Start exists in the partial solution;
HX	Heat exchanging with another heat sink, treating the current architecture as a load to be cooled	Start exists in the partial solution; The last behavior in partial solution is not HX; Load not in partial solution; EXP not in partial solution;
CMP	Compress the heat sink to lift its thermal state (if CMP happens before EXP, then a HX must follow CMP)	Start exists in the partial solution; Total number of CMP in partial solution < c (c is a user specified number, 1 for this study);
EXP	Expand the heat sink for cooling	Start exists in the partial solution; Total number of EXP < e (e is a user specified number, 2 for this study); Load not in partial solution;
WE	Water extraction from air	Selected heat sink is air; The last behavior is EXP;
Load	Load is cooled	Start exists in the partial solution; Load not in the partial solution; The last behavior in partial solution is EXP;
Rec	Re-circulates back to certain points (to start for closed loop, to perform secondary cooling or partially mixing with stream coming into the load for open loop)	Start exists in the partial solution; Load is last behavior in the partial solution is; No same type of Rec exists in partial solution;
End	End of the partial solution, termination condition for a solution in backtracking	Start exists in the partial solution At least one CMP in partial solution; At least one EXP in partial solution; Load in partial solution;

architecture might be cooled by another, and this new one could also be cooled by another new one. If there is no limitations, then there could be infinite number of populated TMS architectures. So to limit the number of generated architectures, it is allowed at most four cooling architecture linked together in this paper, and the final one must be a open-loop architecture, discarding the heat sink used in the final cooling architecture from the current local TMS.

The compatibility of some behaviors listed in the two tables will be described below, while the other obvious ones are not discussed due to space limit of the paper. For the direct heat reject architectures: HX is only compatible to the closed-loop system, because the heat sink needs to be cooled before going back to the reservoir, while assuming heat sinks in open-loop architecture do not need further cooling; Re-circulation to the Start only happens after the load is cooled in a closed-loop system; the current partial solution is complete (End is compatible) when the load is cooled and the re-circulation has been performed. For the refrigeration cycle architectures: HX is used to remove heat from the heat sink, thus it happens when the thermal state is high, that is, it only happens before EXP; If CMP happens before EXP, it is used to lift the thermal state of the heat sink to improve the performance of heat removal, so a HX must follow it to perform the heat removal; the water extraction always corresponds to a expansion process, so WE is compatible when the last behavior is EXP; the load is cooled when heat sinks are at low thermal state, which must happen after EXP; the termination condition (End) is compatible only when the load is cooled, and the EXP and CMP have been performed.

2. *Example of Local TMS Architecting*

The architecture of a cabin ECS, which is a local TMS, is constructed using the proposed method to illustrate the architecting process. The behavioral architecture is constructed first. The process of establishing the behavioral ECS architecture is shown following the backtracking steps. From the starting point, the top level in Fig. 9, the cooling load of the cabin is considered with the regulations. As the regulations [41–43] dictate that the supply air of the ECS should be able to pressurize the cabin as well as to provide enough fresh air as much as 0.55 lb/person/min, the heat sink in the ECS to supply to the cabin has to be compressed air, which leads to the only behavior through refrigeration cycle to provide cooling compressed air. Compressed air has to correspond with a open-loop system with refrigeration cycle. Therefore, the behavioral architecture construction can directly start form the node "Air" which is a child of "Open loop" following the "Refrigeration cycle" node. The preceding behaviors identification can be illustrated in Fig. 10.

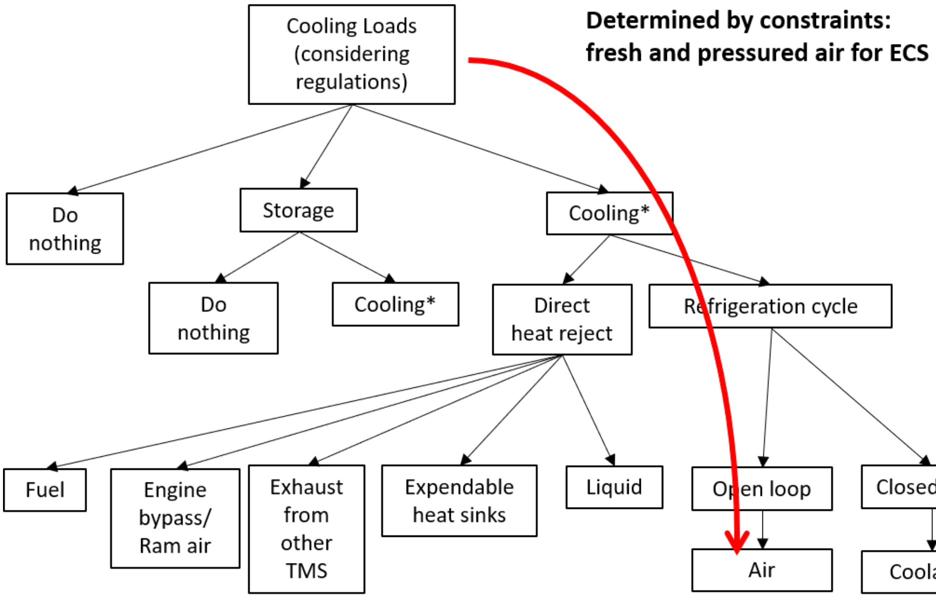

Fig. 10 ECS architecting process from cooling load to the architecture construction starting point

From the last reached node, the behavioral architecture starts to be constructed. Following the backtracking algorithm 1 with the compatibility table 2, the compatible behaviors are enumerated one by one, until the termination condition is triggered. Fig. 11 illustrates an example to construct one solution of the ECS. When one solution is obtained, the backing tracking process starts, and an example is shown in Fig. 12. The last step in the previous solution was done by selecting "End". After backtracking, the "End" is removed, and the other option "Rec" is appended to the partial solution, and then the algorithm continues to append compatible behaviors to the partial solution, until another termination condition is triggered.

As discussed before, each HX acts as a new load to be cooled. For the previously obtained ECS architecture, there are two HX, thus there will be two new loads to be cooled, starting from the top level shown in Fig. 9. And the same backtracking method will be implemented. For the illustration purpose and to avoid the repetition, we could just assume these two loads are cooled by the same type of TMS, and assume the TMS are direct heat reject systems using ram air without loss of generality. The architecting process is illustrated in Fig 13. Thus the obtained overall TMS architecture solution can be shown in Fig. 14

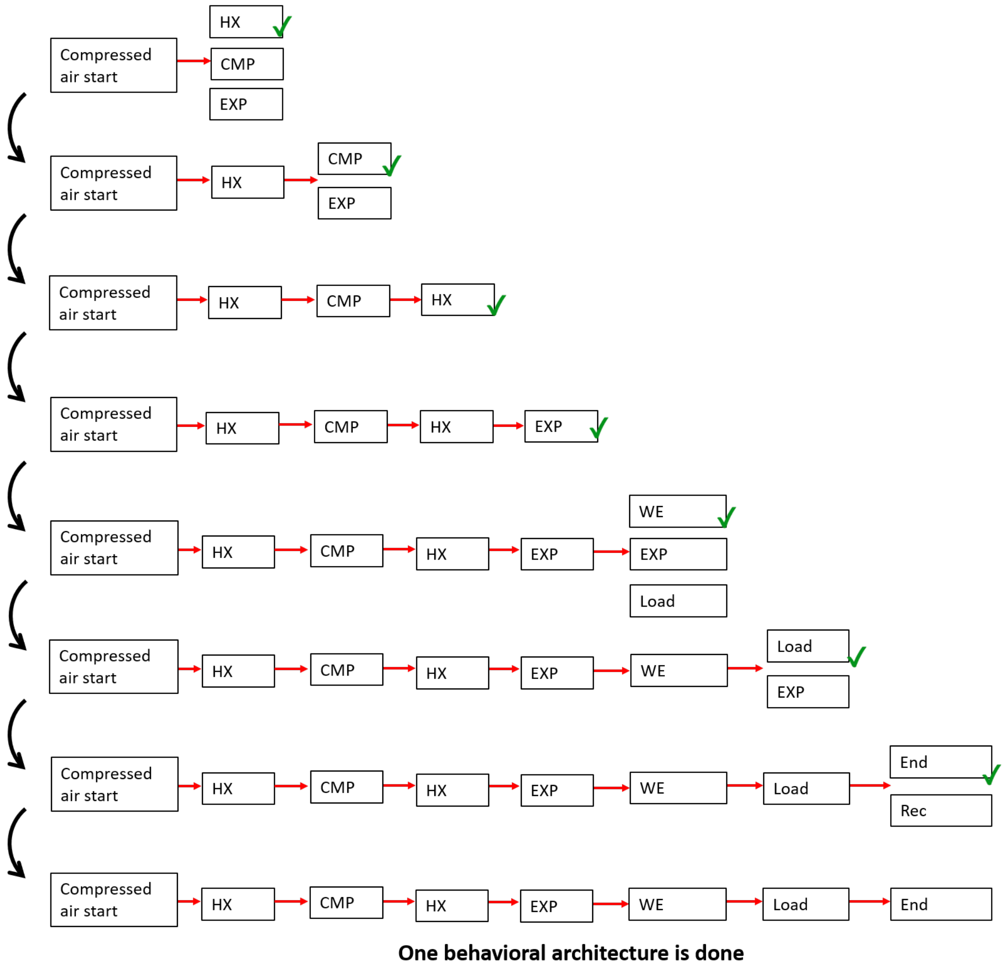

Fig. 11 ECS architecting process

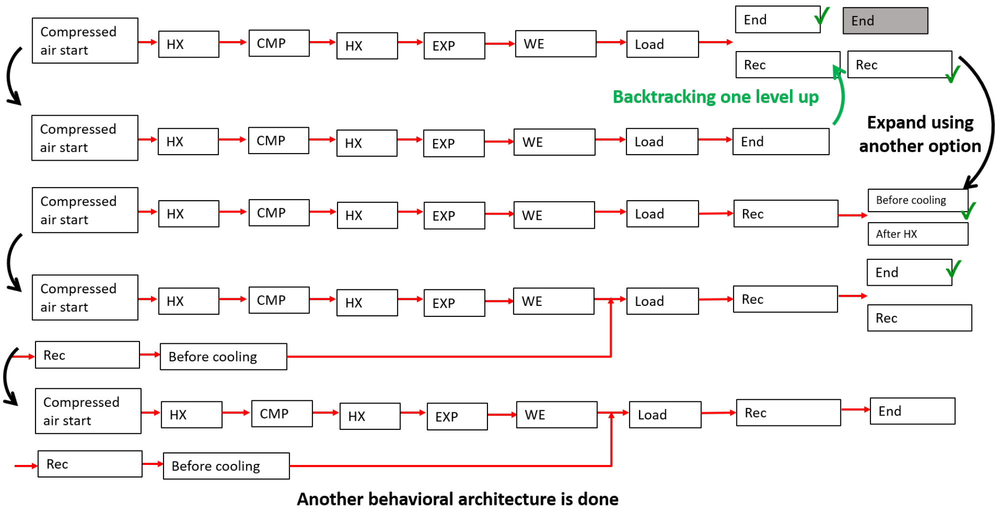

Fig. 12 ECS architecting backtracking example

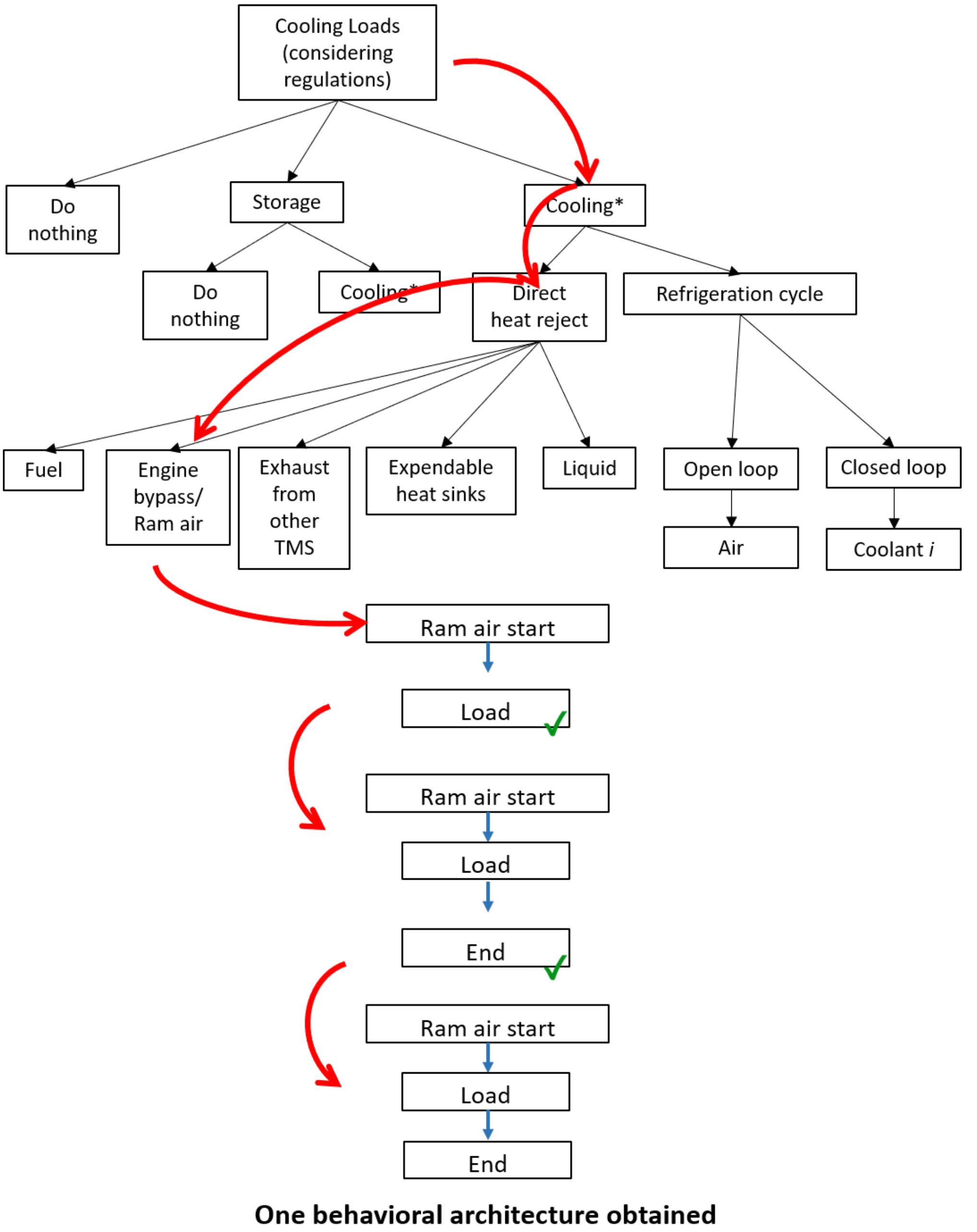

Fig. 13 Example architecting process for a HX in obtained TMS architecture

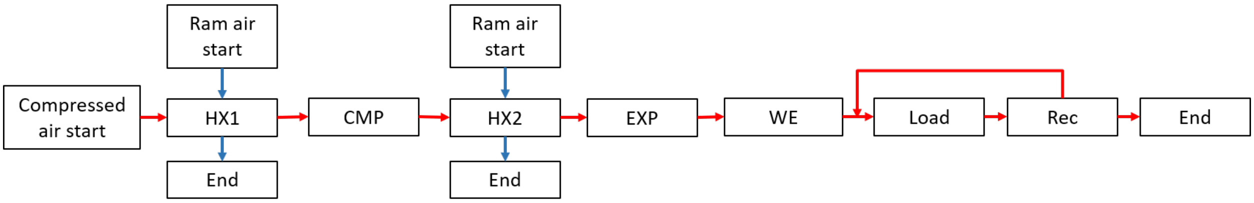

Fig. 14 Overall ECS behavioral architecture example

C. Behavioral to Structural Architecture

From the constructed behavioral architecture, the structural architecture can be created by replacing the behaviors by the components that are capable of performing such functions. The components that can perform the behaviors in the constructed architecture is listed in Fig. 15. Using these components, the behavioral architecture can be converted to a structural architecture, shown in Fig. 16. It should be noted that the same behavior can be performed by different components, thus the same behavioral architecture can generate different structural architectures. However, for simplicity, only one example of the structural architecture is presented here. It should be also noted that the components for each behaviors in this paper are just to demonstrate the capability of the approach. In real applications, users can change these options in terms of preferences or specific requirements.

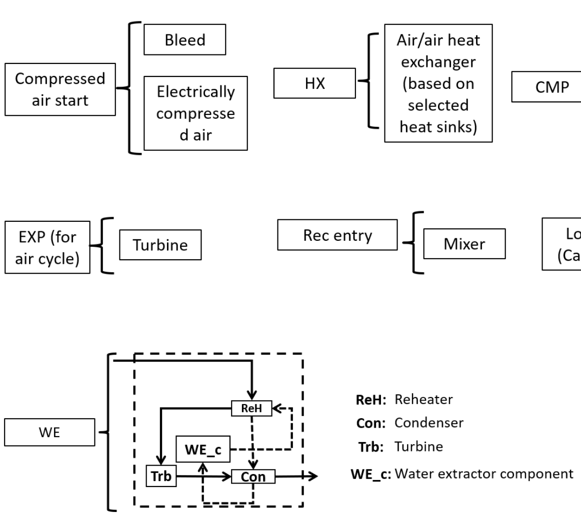

Fig. 15 Components that perform certain behaviors

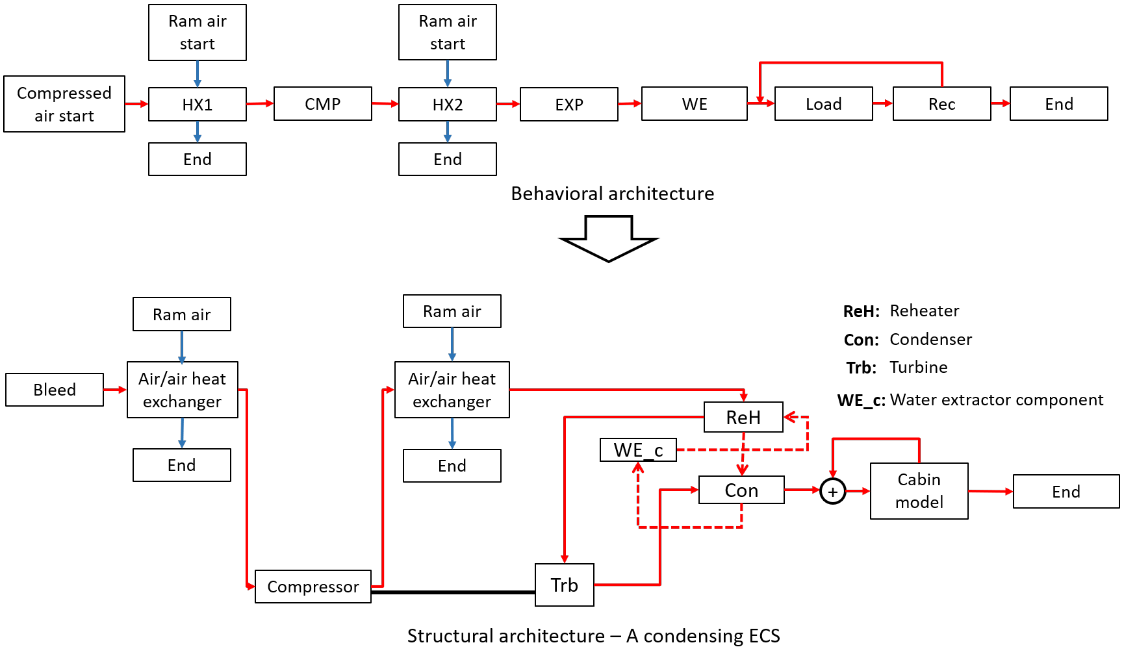

Fig. 16 Behavioral to structural architecture conversion example

D. Global TMS Architecting

1. Behaviors of Global TMS

The global TMS can be interpreted as interactions among each local TMS. Therefore, the variations of the global TMS are created by varying local TMS for each heating or cooling load or interactions among local TMS. Firstly, the local TMS for each load are enumerated by the backtracking method. There are not many constraints on the compatibility when constructing the global TMS. The only constraint is that heat sinks for local TMS cannot be all exhaust. After enumerating the local TMS, then the linkages among local TMS that do not use exhaust and local TMS use exhaust are enumerated, using the same backtracking approach. It should be noted that although there is no specific compatibility constraint except the exhaust one in this paper for the purpose is only to demonstrate the proposed methodology, other compatibility constraints can be added in terms of the actual applications. For example, if certain local TMS uses cryogenic TMS, then TMS that suitable for for other loads might not be compatible to the cryogenic one. Another example is that some loads may not be allowed to be cooled by certain types of exhaust, so the some type of exhaust may not be compatible to some TMS solutions.

2. Example of Global TMS Architecting

An example showing construction of global TMS is presented in this section. In this example, each local TMS is represented by a label such as A 1 standing for TMS architecture for load 1. It is assumed that there are 7 loads (Load 1 to 7) in total. First 7 backtracking steps are corresponded to the selection of local TMS from Load 1 to Load 7. This process is illustrated in Fig. 17, and for simplicity, results of all 7 steps are shown at the same time.

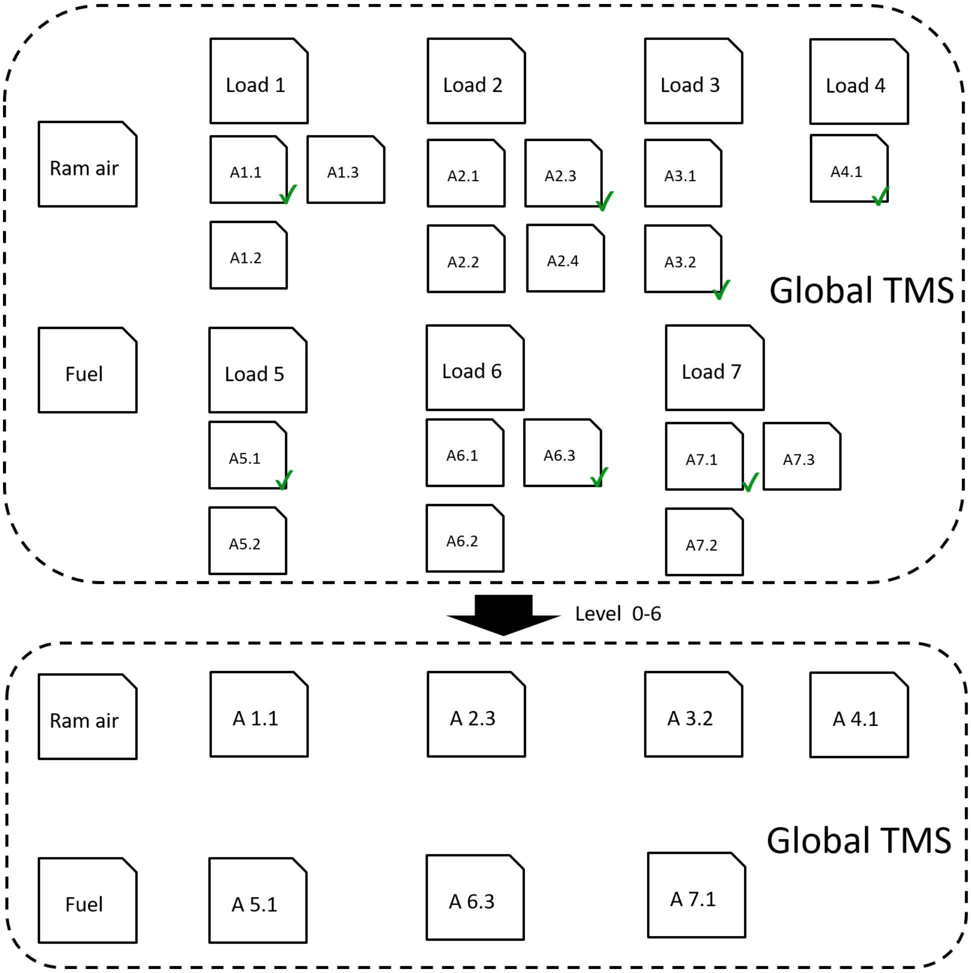

Fig. 17 Selection of local TMS

Assuming A 1.1 and A 6.3 require ram air, A 3.2 and A 5.1 require fuel, A 2.3 requires both ram air and fuel, A 7.1 requires exhaust, and A 4.1 requires nothing. The next backtracking step is to route the ram air, and then to route the fuel, and then to route the exhaust until all options of local TMS and exhaust routes are enumerated. Such interactions architecting is shown in Fig. 18. It should be noted that for this example fuel is not considered as a load to be cooled, but in reality it can serve as a

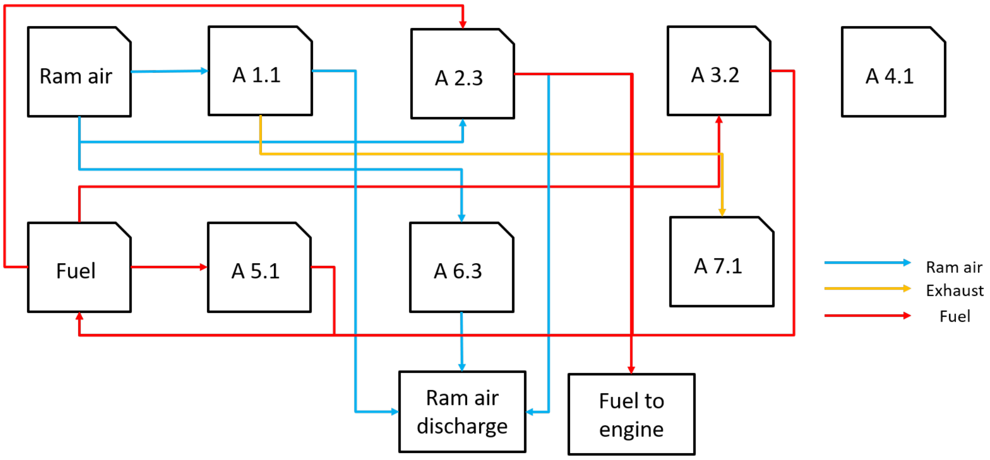

Fig. 18 Interaction architecting for global TMS

The backtracking process in the global TMS is simple so that there is no need for an example to illustrate it. The backtracking process start from the level of routing exhaust since it is the last level. When the options of exhaust route has been fully explored, the process backtracks back to the level of selecting the component for the last load. Then another component is selected for the last load, and interactions are built around the new layout. Such process will continue until all options of the local TMS and interactions among them are tried out.

IV. Validation Cases

The cases to be architected to validate the capability of the proposed method are presented in this section. Two aircraft concepts are selected for the validation purpose: a 305 pax traditional commercial aircraft and an electric aircraft with TeDP system. The corresponding aircraft design specifications and the selected heating and cooling loads are shown in the following subsections. It should be noted that typical heating or cooling loads for each configuration are selected only for the validation purpose. The heating or cooling loads are subject to change if there are specific requirements for the actual applications.

A. Traditional Commercial Aircraft

The aircraft design specification is listed in Table 3, which has been used to conduct ECS studies by the authors in the previous work [44]. The available heating sources are the high pressure compressor (HPC) extracted bleed and electrical heating, and the available heat sinks are the cooled HPC extracted bleed, ram air, fan bleed, fuel, oil, refrigerants, and cooling fluid. The major components need to be cooled are: cabin, avionics, hydraulics, fuel, engine oil, and generators (either mounted on the engine or the auxiliary power unit (APU)). The major components need heating are: cabin and wing ice protection system. Since it is the traditional configuration, cooling and heating options that only appear in MEA or AEA are eliminated, such as electrically compressed ram air as a heat sink and electric heating mat for wing ice protection.

B. Turbo-Electric Distributed Propulsion System

The design specifications of the TeDP concepts are shown in Table 4, of which the model was constructed by the authors in the previous work [17] for the ULI program. This configuration has eight electric fans to produce the thrust. A turboshaft engine is mounted on each wingtip to produce the required electric power. The available heating sources are the HPC extracted bleed, electrical heating, and electrically compressed ram air. The available heat sinks are the

Table 3 Design specifications of the traditional aircraft

Parameters	Value
Passenger capacity	305
Design payload weight, lbm	64 050
Design range, nmi	7500
Cruise Mach number	0.840
Maximum cruise altitude, ft	43 000
Maximum payload weight, lbm	125 500

cooled HPC extracted bleed, electrically compressed ram air, ram air, fan bleed, fuel, oil, refrigerants, cooling fluid, and PCM. The major components need to be cooled are: cabin, avionics, hydraulics, fuel, oil, battery, buses and control panels, generators (mounted on the turboshaft engines). and motors to drive the electric fans. The major components need heating are: cabin and wing ice protection system.

Table 4 Design specifications of the TeDP system

Parameters	Value
Passenger capacity	78
Design payload weight, lbm	18 060
Design range, nmi	1980
Cruise Mach number	0.80
Maximum cruise altitude, ft	41 000
Maximum payload weight, lbm	23 350

V. Results and Validation

The generated local TMS and global TMS are shown and validated in this section. Due to the space limit of the paper, three local loads are selected to validate the capability to generate both intuitive and non-intuitive architectures of local TMS: cabin for a traditional aircraft; motor for TeDP; and battery for TeDP. Traditional and TeDP aircraft are both selected to validate the capability to generated global TMS.

A. Results and Validation of Local TMS

There are some user specified requirements to the local loads: cabin must be cooled by pressurize air according to regulations [41–43]; motor must be directly cooled by oil; battery can be cooled by any type of methods; if a open-loop refrigeration cycle with air is used to cool a certain load, the ECS for the cabin will be used, so there cannot be another independent air cycle machine to produce cold air. It should be noted that these constraints are only used for testing purpose. Users can remove any of them or add more in terms of the actual application.

1. Cabin

There are in total 682776 generated TMS architectures for the cabin load. All of them use bleed extracted from the engine as the supply air. Because of this large number of generated architectures, only a few are selected to compare with the existing architectures to demonstrate the proposed methodology is capable of generating conventional TMS architectures. And a few are selected to demonstrate the proposed method is also able to generate non-intuitive but reasonable TMS architectures.

The generated architectures are stored as a set of lists, thus to select generated conventional architectures, conventional architectures from literature were firstly converted into lists and then were directly searched in the solution set to check if they exist. Three-wheel and four-wheel ECS from Parrilla's study [45] are used for this validation. The generated architectures are shown in Fig. 19 and Fig. 20, which match the exact architectures shown in the reference [45].

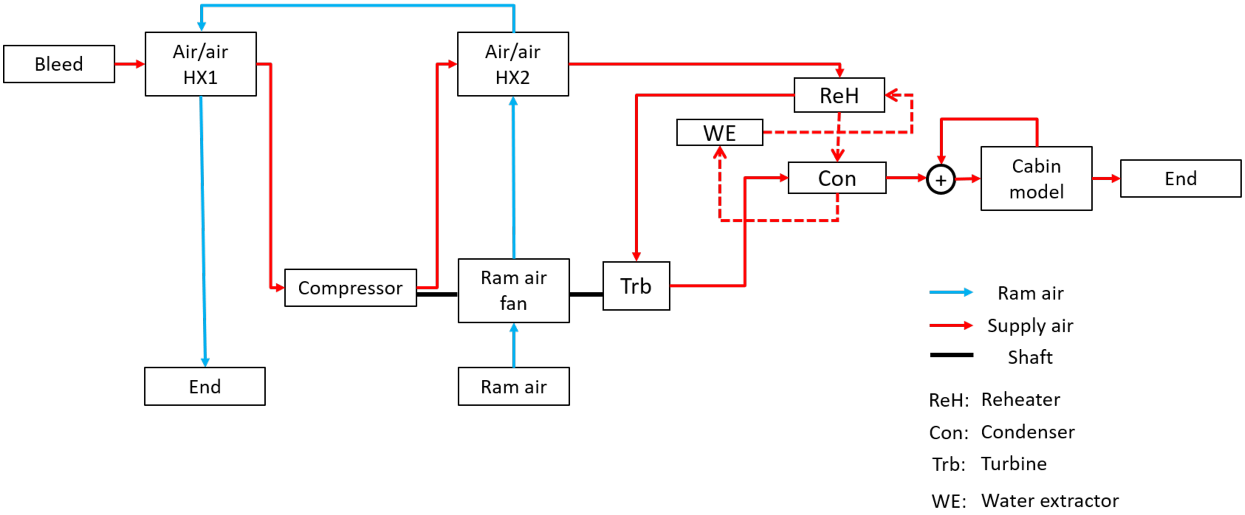

Fig. 19 Generated three-wheel TMS architecture

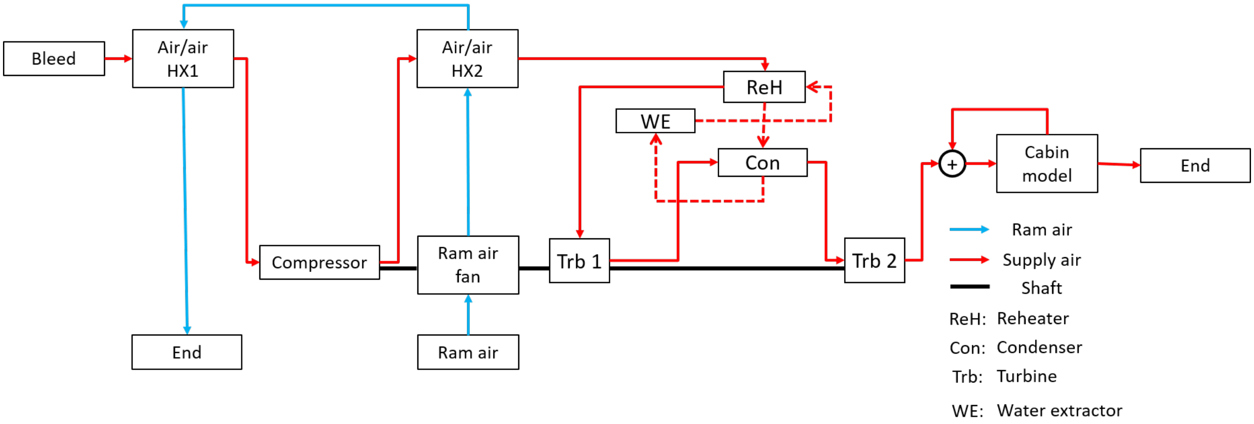

Fig. 20 Generated four-wheel TMs architecture

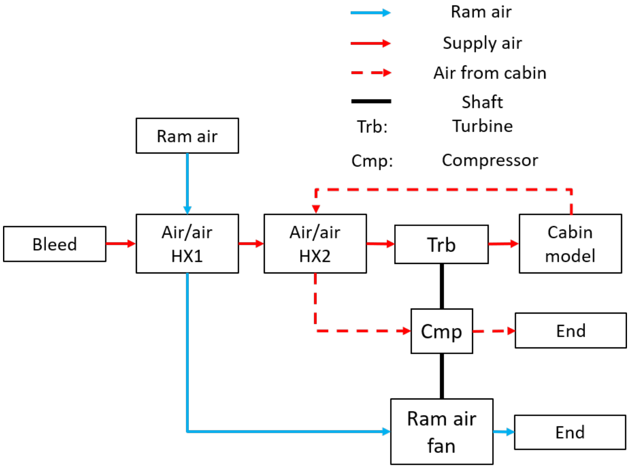

Fig. 21 Novel TMS following reversed bootstrap to cool cabin

Some novel and non-intuitive TMS architectures for the cabin are also generated. For example, as shown in Fig. 21, which has not been seen but also follows the basic reversed bootstrap refrigeration cycle [1]. Another example is illustrated by Fig. 22: an ECS with vapor cycle cooling the re-circulation path, which has been studies by Seki [37] and Staak [36].

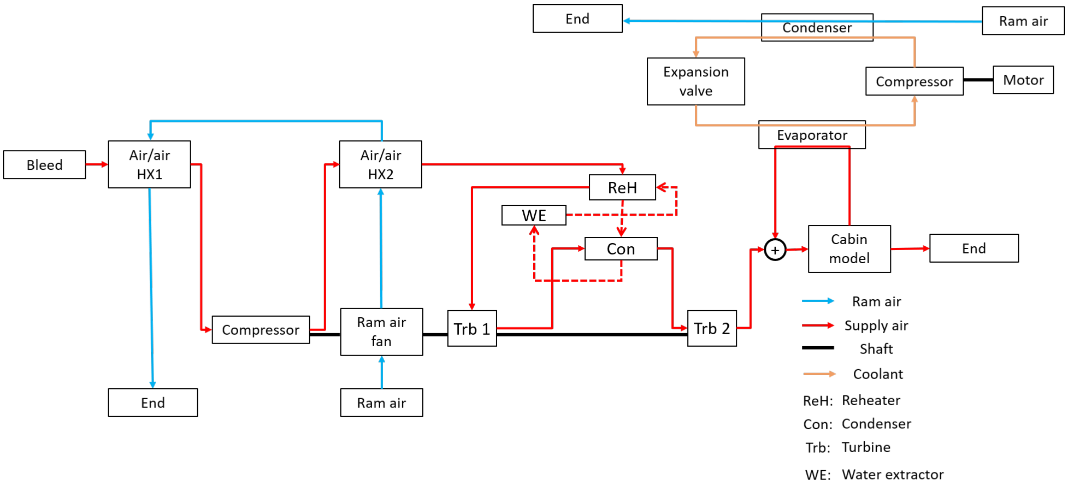

Fig. 22 Novel ECS with vapor cycle cooling re-circulation path

2. Motor

For motor as a cooling load, which only uses oil for cooling, there are 7921 architectures generated. Among these generated architectures, conventional architectures have also been found. One generated TMS cools the motor by oil, and then the oil is cooled by fan case air, as shown in Fig. 23, which corresponds to the architecture shown in Perullo's work [17]. The other generated TMS cools the motor by oil, and then the oil is cooled firstly by fan case air and fuel, as presented in Fig. 24, which is similar to the oil loop in Moir's book [2]. Thus, these two generated TMS architectures are found similar to conventional ones. An example for a novel TMS is also shown in Fig. 25, which incorporates a PCM to store partial generated heat. The author has also conducted a study on a similar subject [31].

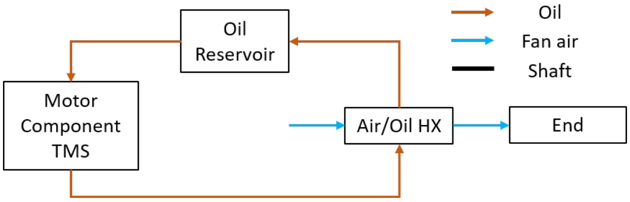

Fig. 23 Conventional motor TMS 1

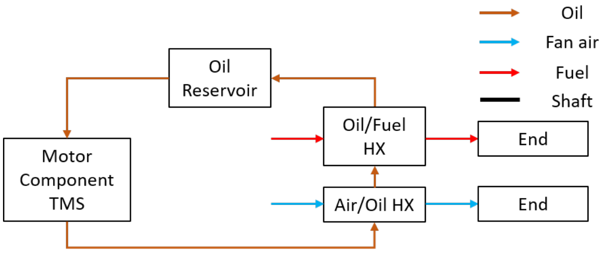

Fig. 24 Conventional motor TMS 2

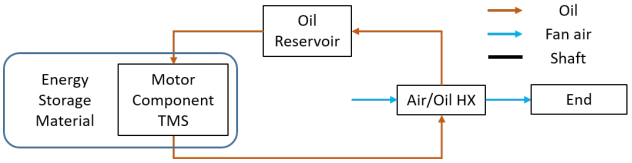

Fig. 25 Novel motor TMS with PCM

3. Battery

For battery as a load, which incorporates all possible solutions, there are in total 205209 architectures that have been generated. An example for the conventional one is shown in Fig. 26, which uses a closed-loop cooling oil as heat sink, and the oil is cooled by ram air. Here also presents two examples for the novel TMS architectures: one uses the air from the ECS as shown in Fig. 27, and the other one uses the exhaust from the cabin as shown in Fig. 28.

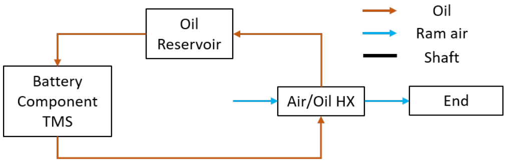

Fig. 26 Conventional battery TMS

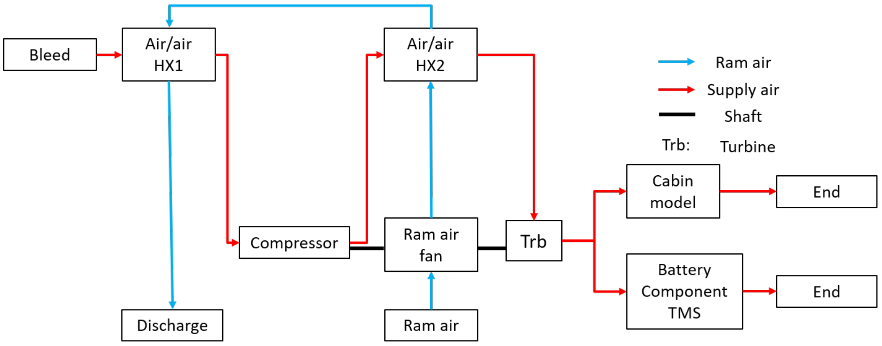

Fig. 27 Novel battery TMS using air from ECS

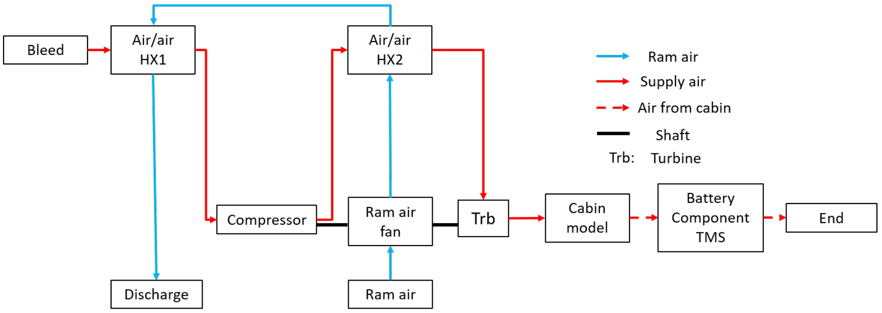

Fig. 28 Novel battery TMS using exhaust from cabin

From the architectures generated for selected local loads above, it can be concluded that the proposed architecting methodology is able to populate both intuitive and non-intuitive local TMS architectures.

B. Results and Validation of Global TMS

The cooling loads for the traditional configuration aircraft and TeDP configuration aircraft are used to generate the global architectures. For the traditional configuration, as discussed in the previous section, the cooling loads are cabin, avionics, hydraulics, fuel, engine oil, and generator. An example of the obtained global TMS is shown in Fig. 29, which is consistent with the one in Moir's work [2].

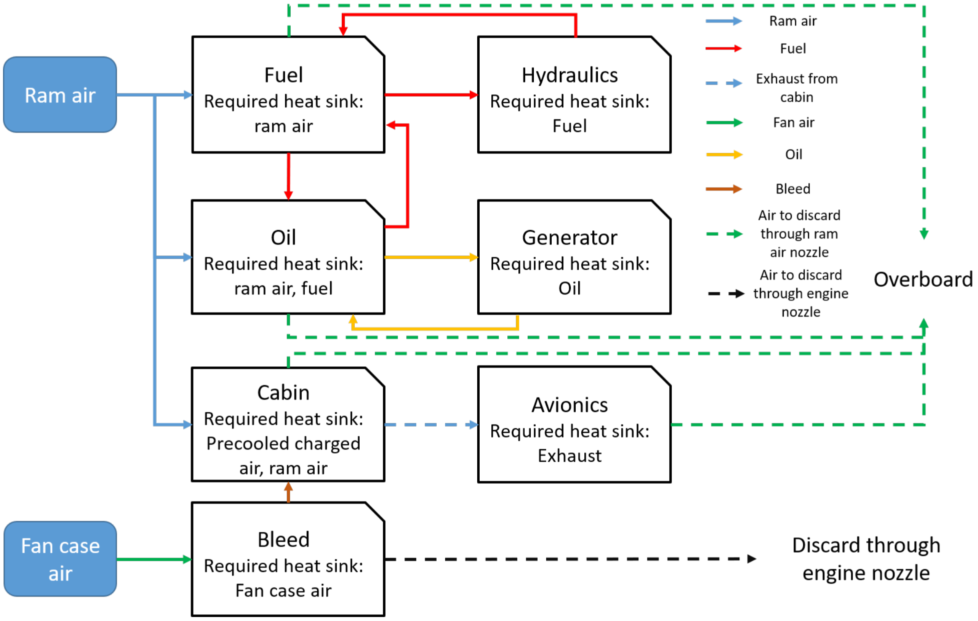

Fig. 29 Generated global TMS for traditional configuration aircraft

For TeDP configuration, the selected local cooling loads are cabin, avionics, hydraulics, fuel, oil, battery, generator and motor. One generated global TMS is found to be similar to the one in an existing study [17], where motor is cooled by oil loop, and battery is cooled by ECS parallel to the cabin. This generated global architecture is shown in Fig. 30.

It should be noted that when any of the local TMS is replaced with a non-intuitive local TMS architecture, then a non-intuitive global TMS architecture will be populated. Therefore, there is no much need to show another global TMS that is different from existing ones. Thus, the presented examples are sufficient to demonstrate the proposed methodology is capable of generating both intuitive and non-intuitive global TMS architectures.

VI. Conclusions and Future Work

This paper proposes a methodology to systematically populate both intuitive and non-intuitive TMS architectures at global and local levels. The populating process is realized by a behavior-based backtracking approach. This proposed method based on the behaviors that follow the fundamental physics to firstly construct behavioral TMS architectures, and then convert the behavioral architectures to structural architectures by enumerating potential components that ran realize the function of each behavior. The backtracking algorithm is used to systematically enumerate TMS solutions while ensuring the compatibility of each behavior.

Cooling loads for traditional configuration and TeDP configuration aircraft are used to validate the the proposed methodology. From populated TMS architecture examples at both local and global level, it is demonstrated the proposed methodology is able to populate both intuitive and non-intuitive TMS architectures, of which the number is much larger than pre-selected ones in existing literature. Therefore, the capability of the proposed architecting methodology is validated.

One difficulty regarding the current proposed methodology is that the number of generated TMS architectures is too large to conduct detailed analysis for each of them. Therefore, an approach to rapidly filter out infeasible and non-optimal

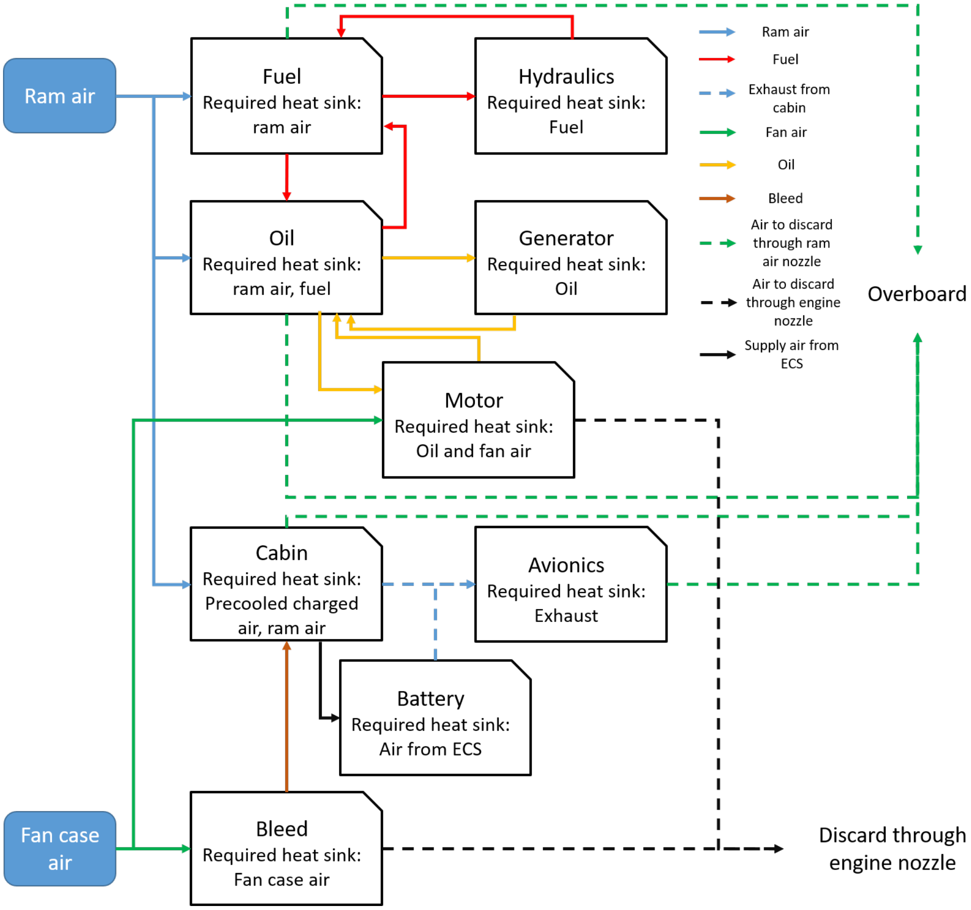

Fig. 30 Generated global TMS for TeDP configuration aircraft

TMS architectures is required before moving into the optimization and sizing phase. The authors are currently working on a non-supervised machine-learning-based method to realize such filtering function. After achieving the capability of rapid filtering, another future research avenue is to integrate this TMS architecting approach with aircraft conceptual design, and investigate the decision making on selection of optimal TMS architectures in terms of different aircraft types.

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