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Cool Planes for Hot Missions: Early but Effective Aircraft Thermal Management Design

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Multi-role fighter aircraft are facilitated by operational and platform capabilities that are in turn supported by basic aircraft function. Thermal management (TM) is a basic aircraft function. Effective TM design at the aircraft concept stage can determine if it can support the intended operational and aircraft capabilities early in the aircraft project. In this study, a three-session workshop with a cross-functional team for TM design was conducted at Saab AB. The outcomes from the workshop resulted in a framework for a detailed understanding of the steps to be carried out iteratively for TM design by a cross-functional team. It also provides the dependencies for these steps and the various functional groups that need to be involved in each step. The steps can be used to iterate TM design at the aircraft concept stage and understand the implications on aircraft and operational capabilities. Further, the workshop methodology presented can be used to obtain similar frameworks for design of other basic functions at the aircraft concept stage.

I. Introduction

Fighter aircraft are typically multirole platforms. The Saab Gripen aircraft is designed to be a fighter, attack, and reconnaissance aircraft. These roles are facilitated by operational and platform capabilities that are in turn supported by basic aircraft function. This is shown pictorially in Fig. 1. Typical basic aircraft functions include aerodynamics, airframe structure to sustain loads, flight mechanics and control, navigation, power management, propulsion, and thermal management. In this paper, operational capability entails the missions the aircraft is designed to carry out. While platform capabilities entail the characteristics it is designed to have to support the various aircraft roles. When basic aircraft function does not perform up to specification then operational and aircraft capabilities are impacted. Changes were required to a fighter aircraft mission due to thermal management (TM) challenges it was facing as noted in Ref. [1] and Ref. [2]. Therefore, using ISO 15288 to define the aircraft life cycle, this paper proposes that basic aircraft function design should commence at the aircraft concept stage. This could result in determining if a basic function can support the intended operational and aircraft capabilities early in the aircraft project.

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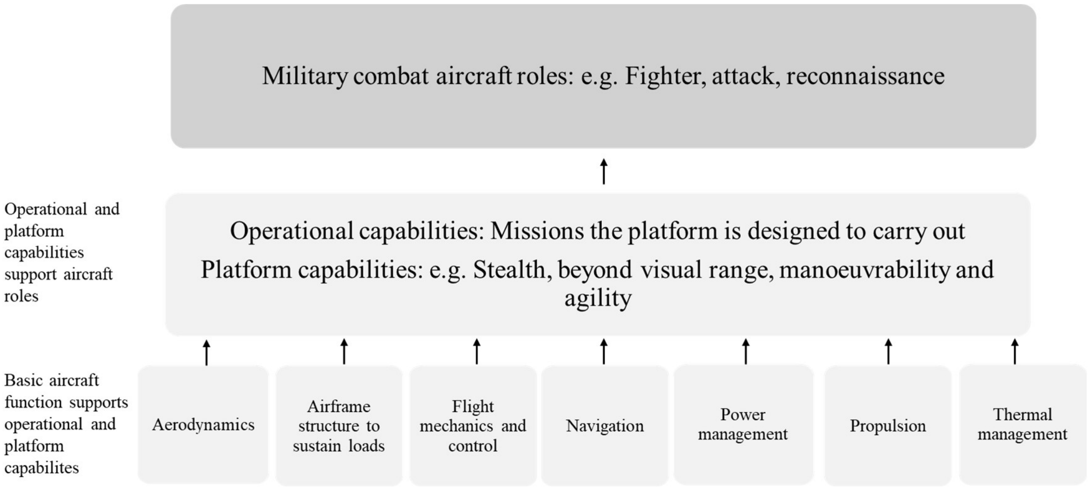


Fig. 1 The hierarchy of support for roles of military combat aircraft.

The demand for on-board cooling power (kW) has increased in recent years but Ref. [3] and Ref. [4] noted that there are still only two options for terminal heat sinks, air (ram or engine fan) and fuel. Terminal heat sinks are the destination for onboard waste heat [5]. Cooling power demand has increased due to greater use of more electric technologies in aircraft [6-13]. There is an additional challenge for fighter aircraft with greater demand for cooling power from tactical systems [3, 6, 10, 14, and 15]. Aircraft TM is further challenged by the decrease in heat sink capability due to platform design aspects. Increasing use of composite materials for airframe skin over traditional metals impedes the dissipation of waste heat through skin [7, 8, 11, 12, 15-21]. Infrared (IR) and radar cross-section (RCS) signatures are minimized to improve aircraft stealth by minimizing the cross-sectional areas of ram air intakes [7, 11, 15-19]. This reduces the amount of waste heat that can be dumped overboard through ram air. All these contemporary challenges create a strong need to commence TM design at the aircraft concept stage. This need is further exacerbated by the fact that TM can greatly impact mission operability as noted in Ref. [1] and Ref. [2] and it can impact aircraft performance as noted in Ref. [7]. Therefore, TM design must commence at the aircraft concept stage to determine if it can support operational and aircraft capabilities for various platform design constraints.

In this study, the concept TM refers to the acquisition, transport, and rejection of waste heat as considered in Ref. [4]. TMS refers to the aircraft systems that are responsible for TM. Typically, they are the aircraft environmental control system (ECS), the fuel system, and any other cooling means. While TM design refers to the process of designing and analyzing an aircraft thermal management system (TMS).

The need for TM design to be considered early in an aircraft project has been noted in Ref. [22] and Ref. [23]. In recent years, a variety of methods for TMS architecture generation [21, 23] and TMS modelling and simulation [7, 8, 9, 11, 12, 14, 16, 19, 22, 24, and 25] have been presented. However, aircraft are complex systems with several interdependencies that are typically not defined at the concept stage [26, 27]. Obtaining the information to populate these methods may require several different steps at an aircraft developer like Saab. Further, at each step several different functional groups might be involved. The order that information is obtained in must be determined to conduct design iterations more efficiently. Therefore, TM design at the aircraft concept stage must entail what information is needed, in what order, and the various functional groups needed to provide the information and those that are impacted by it. Effective TM design should ensure that TMS architectures can be analyzed to determine if the system can support operational and aircraft capabilities.

A. The Purpose of the Paper

The primary purpose of this paper is to demonstrate what is required for effective TM design at the aircraft concept stage. The second purpose is to demonstrate a framework to enable effective iterative TM design at the aircraft concept stage. The framework can help an aircraft developer determine if a TMS can support the intended operational and aircraft capabilities at the concept stage. To fulfil these purposes, a workshop was conducted at Saab with a cross-functional team for a pre-defined scenario for TM design.

B. Outline of the Paper

First, a detailed description of the workshop is provided in Section II. Then, the outcomes of the workshop and the framework for iterative design are presented in Section III. Finally, the conclusions of this study are summarized in Section IV.

II. Methodology

The methodology for this study consisted of a cross-functional workshop for TM design. The workshop was an efficient method to fulfill the goals of this study. It was chosen over other data collection techniques like individual or group interviews with experts from various functional groups. A workshop allowed the cross-functional team to work together to determine the order of the information and the various functional groups needed to provide the information for TM design. The workshop had three main phases, the set-up phase, the execution phase, and the post-workshop phase. The various steps under these three phases are described in this section and are summarized in Fig. 2

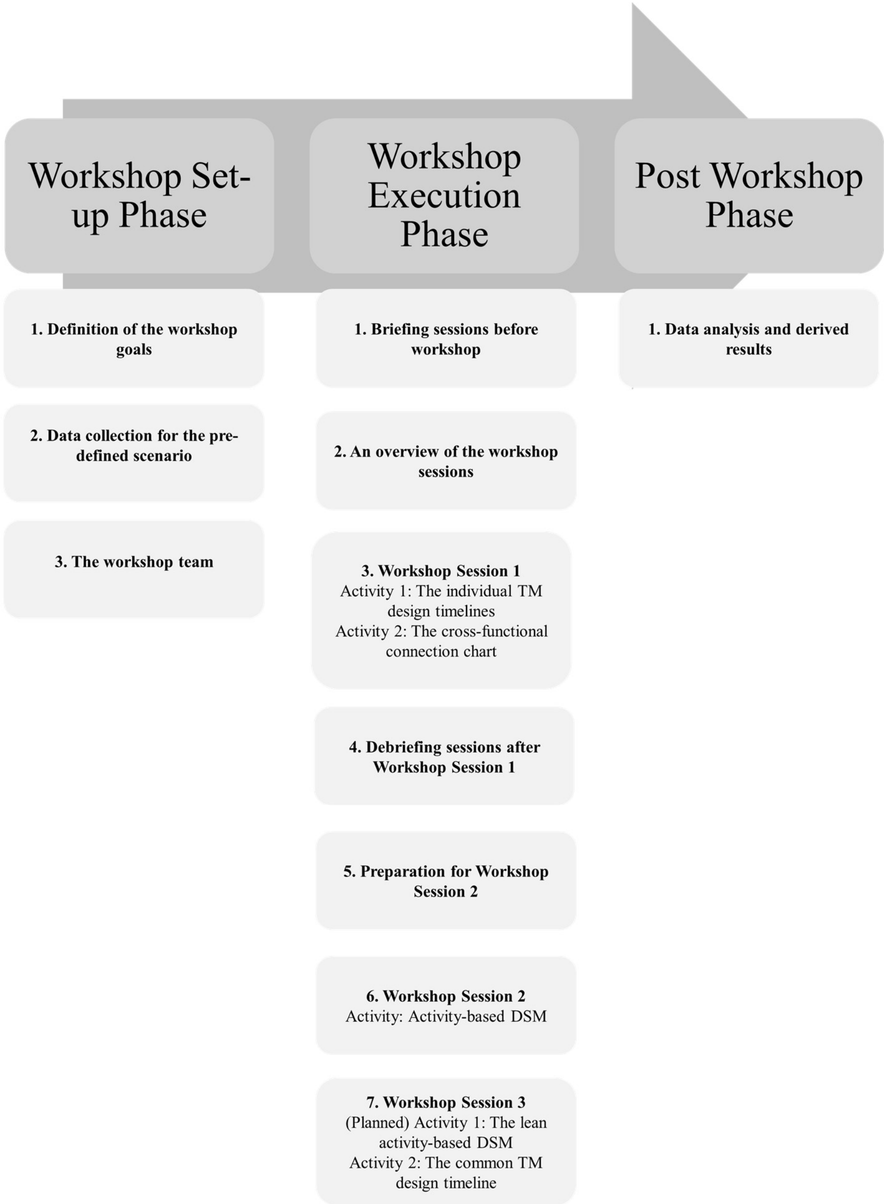


Fig. 2 A summary of the steps of the three workshop phases, namely, the workshop set-up phase, the workshop execution phase, and the post-workshop phase. TM is thermal management and DSM is design/dependency structure matrix.

A. Workshop Set-up Phase

The workshop set-up phase consisted of three steps. The first step entailed defining the workshop goals to align with the goals of the study. The second step details the data collection conducted to define the scenario for the workshop. And the third step describes the workshop cross-functional team. The three steps are described chronologically in this sub-section.

1. Definition of the Workshop Goals

To fulfill the goals of the study the main goals of the workshop were defined as follows:

1) To create a common timeline for the steps to be carried out for TM design at the aircraft concept stage.

2) To understand the dependencies between the various steps of the TM timeline.

3) To determine the various functional groups that need to be involved in each step of the TM timeline.

These goals were accomplished through a series of workshop sessions.

2. Data Collection for the Pre-defined Scenario of the Workshop

Following the definition of the workshop goals, the set-up phase continued with data collection at Saab and through relevant literature on aircraft TM. All data collected during this step became part of the information for the workshop pre-defined scenario. Data collection through semi-structured interviews was conducted with four experts at Saab. These experts included a product manager, an operational analysis expert, an aircraft engine and fuel system expert, and an aircraft ECS expert.

All four experts were interviewed separately. The interviews were conducted following the order in which the experts are listed below. The first (and second) question posed to each expert was formulated specifically for each expert. Pre-formulated questions for the third and fourth expert were based on the response to the pre-formulated questions for the second expert. With each interview, further questions ensued following the response of each interviewee to their respective pre-formulated questions. All interviews adopted an informal discussion format without audio recordings and all interviews were conducted by the first author only. Handwritten notes were recorded during each interview. Following each interview, further reflections were noted and written by the first author to complete the interview notes. The pre-formulated questions for each expert were as follows:

1) Product Manager:
What capabilities are of interest for future fighter aircraft?
What is product management responsible for at Saab?

2) Operational Analysis expert:
What are the worst operating conditions for a future fighter aircraft from a thermal management perspective?
Could you please help me (first author) create a mission consisting of these operating conditions?

3) Aircraft engine and fuel system expert:
For the mission provided by the operational analysis expert, what is the fuel mass flowrate for the worst operating conditions for a fighter aircraft?

4) Aircraft ECS expert:
Could you please provide me (first author) with the cooling power (kW) required for a future fighter aircraft?
Could you also provide me with a list of consumers of cooling power?

Based on the response to the pre-formulated question, follow-up questions for the product manager were as follows:

1) What does a lightweight and agile capability entail in terms of the physical airframe?
2) How would a beyond visual range (BVR) capability be physically represented in the airframe?
3) How would a stealth capability be physically represented in the airframe?

Table 1 summarizes the response from the product manager for the aircraft capabilities considered for the pre-defined scenario. The aircraft in the pre-defined scenario has three capabilities, namely stealth, maneuverability and agility, and BVR. Physical design aspects impacting TM design are considered for each of these capabilities. A stealth capability entails minimizing IR and RCS signatures and therefore the ram air inlet and outlet cross-sectional areas are to be minimized. From a TM design perspective this would reduce the terminal heat sink capability of the aircraft since the amount of waste heat (kW) that could be dumped overboard through ram air would be lower. Maneuverability and agility entails minimizing the weight and volume of subsystems and maximizing the use of composite materials for airframe skin. From a TM design perspective, this would entail minimizing the weight and volume of the ECS and other localized cooling means. Also, maximizing the use of composites for skin would reduce the heat sink capability of the aircraft. A BVR capability entails maximizing the use of mission-critical systems and thereby maximizing the electrical and cooling power demand (kW) from these systems.

Table 1 Physical design aspects related to aircraft capabilities impacting thermal management (TM) design.

Aircraft capability	Physical design aspects related to aircraft capabilities that impact TM design
Stealth	• Minimize platform infrared and radar cross-section signatures and thereby minimize ram air inlet and outlet cross-sectional area
Maneuverability and agility	• Minimize weight and volume of subsystems • Maximize use of composite materials for airframe skin
Beyond visual range	• Maximize use of mission-critical systems hence maximize electrical and cooling power demand (kW) from these systems

The mission profile and data provided by the operational analysis and fuel system experts is shown in Fig. 3. The mission is to take place in international standard atmosphere ISA+30 conditions. Note that only the three mission segments that are most important from a TM perspective, are populated with mission data. Mission data is provided in terms of altitude (m), Mach number, fuel mass flow rate (kg/s), and time spent in each segment in minutes. Finally, Table 2 summarizes the cooling power demand for both flight critical and mission critical systems for two scenarios for the years 2030 and 2040. In this study, it is assumed that the total cooling power demand is to be met throughout the three mission segments most important from a TM perspective.

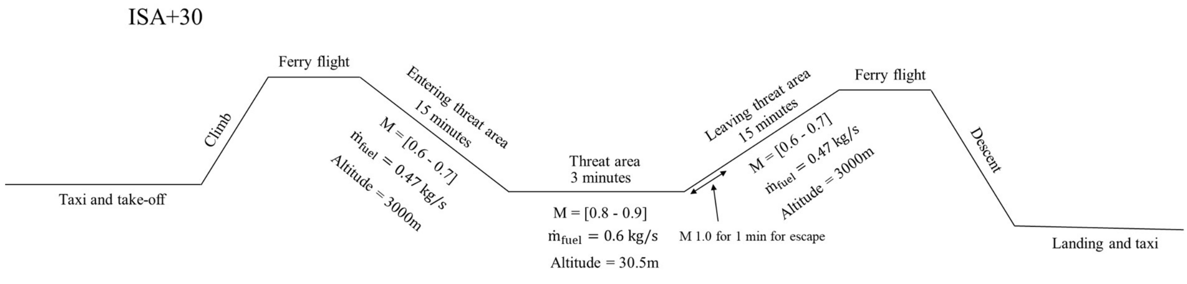


Fig. 3 The mission profile for the workshop pre-defined scenario. ISA is international standard atmosphere, M is Mach number, and $\dot{m}_{fuel}$ is fuel mass flow rate.

Table 2 Cooling power demand for flight critical and mission critical systems for two scenarios, year 2030 and 2040.

Scenario	Year	Cooling power demand from flight critical systems (kW)	Cooling power demand from mission critical systems (kW)	Total cooling power demand (kW)
1	2030	65	50	115
2	2040	75	100	175

Following on from the interviews at Saab, additional data were collated mostly from previous research conducted by the first author. This included what is entailed in a TMS for the workshop scenario, and the architectures for the fuel system and ECS. Ref. [26] adopted the system thinking approach by Ref. [28] to define the boundary for a fighter aircraft ECS in relation to other system dependencies. This approach was adapted for this study to define the TMS boundary. The entities in the TMS boundary include the ECS, the fuel system, and other local cooling means as shown in Fig. 4. The TMS provides to its consumers listed on the left-hand side of the boundary. This list was created with the response provided from the aircraft ECS expert and [26]. Providers to the TMS are listed on the right-hand side. The ECS was adapted from [26] and the fuel system architecture was adapted from [29]. These architectures are shown in Fig. 5 and Fig. 6. From Fig. 4 it can be noted that there are several TMS consumers that require pressurized air indicated by the green bracket and therefore the air cycle machine (ACM) that is part of the ECS can provide the required pressurized air. The other consumers that demand cooling power (kW) that are flight critical but do not require pressurized air can be cooled by transporting waste heat from these systems to the fuel system heat exchanger. The heat can be sunk into the fuel before it is burned in the engine. The mission-critical systems indicated by the purple bracket in Fig. 4 can be cooled by the VCS as indicated in Fig. 5. If any consumer cannot be provided cooling power by the ECS or fuel system or pressurized air by the ECS due to routing of pipes in the aircraft then localized cooling means will be required. Therefore, the ECS, fuel system, and other localized cooling means collectively provide to the consumers of the TMS. On the other hand, electrical power will be required to run the electric motor that drives the compressor of the VCS, bleed or ram air will be required to supply the ACM. Engine fan or ram air or even fuel can be used as a heat sink fluid to the condenser of the VCS. Therefore, the TMS may depend on all or some of these entities to function.

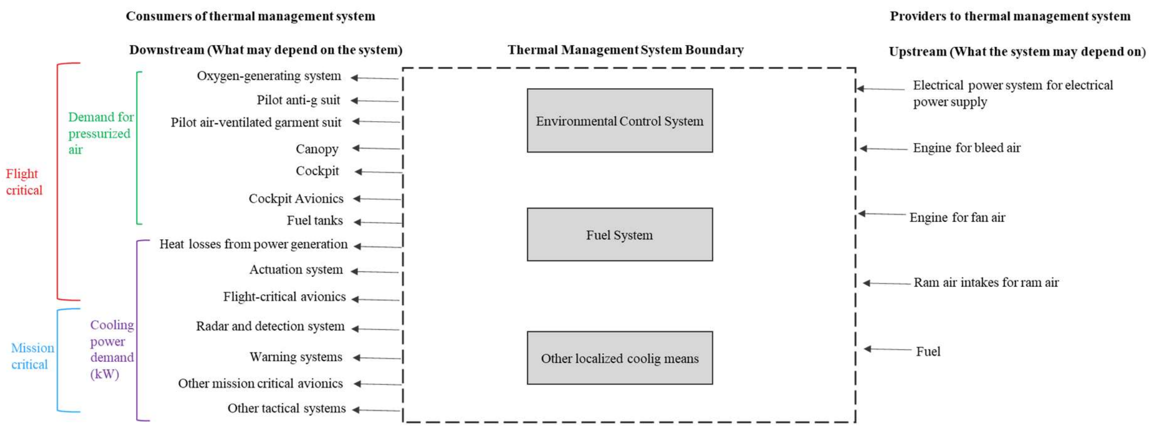


Fig. 4 The system boundary, the providers (what the system may depend on) and the consumers (what depends on the system) for the aircraft thermal management system for this study.

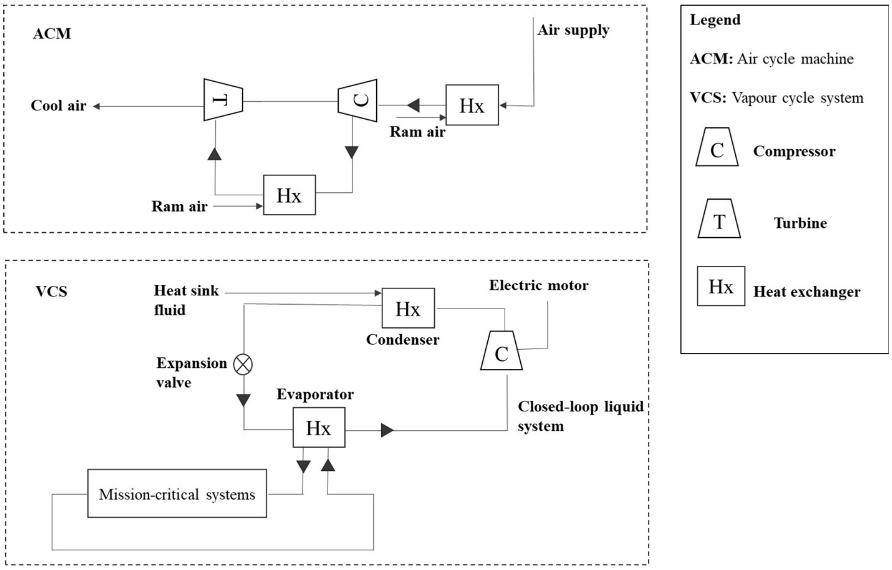


Fig. 5 The environmental control system architecture for this study that has been adapted from [26].

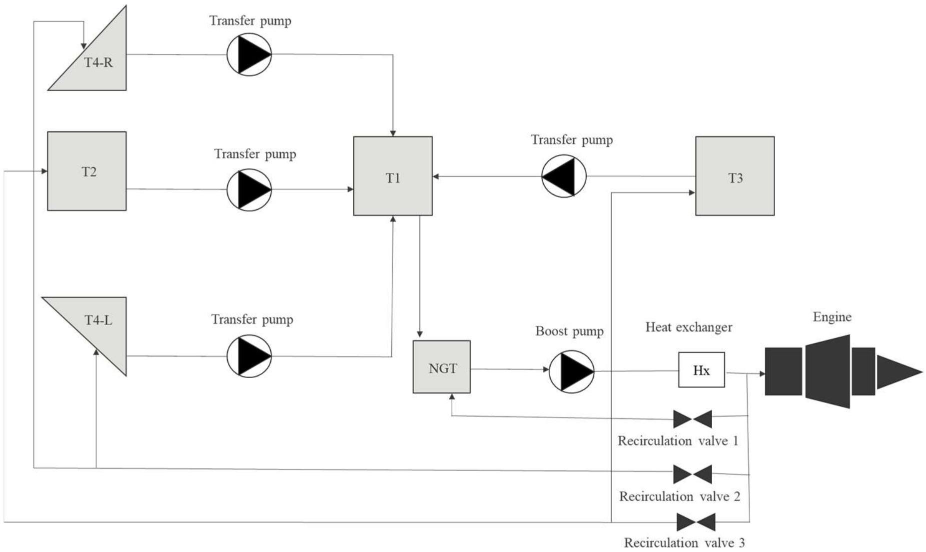


Fig. 6 The fuel system architecture for this study that has been adapted from [29]. T1, T2, and T3 represent the fuselage fuel tanks. T4-L and T4-R represent the left- and right-wing fuel tanks and NGT represents the negative-g tank (the tank used during inverted flight).

Finally, the aircraft type chosen for the workshop scenario was a single-engine, single-seater manned fighter aircraft since this was also used in [26]. The engine type chosen was for conventional take-off and landing with a maximum thrust of 19kN. All the data described in this section formed the pre-defined scenario for the workshop.

3. The Workshop Team

The workshop team consisted of a total of 11 participants, and this is shown in Fig. 7. The first and second author served as the main and co-facilitator of the workshop, respectively. There were two inactive participants serving as observers. Finally, there were seven active participants that made up the cross-functional TM design team and conducted the workshop activities. Each active participant played a different expert role as noted in Fig. 7. Their workshop roles were chosen based on their current and past roles within Saab and external to Saab. The definition of the workshop roles and design levels each expert represented was based on data collected for the pre-defined scenario.

There were five different aircraft project design levels used in the workshop, namely, product, operational, aircraft, subsystem, and component. The product level represents the aircraft as a product to the customer. The product includes the complete package from customer requirements to development into operational, maintenance, and upgradability support of the aircraft. The definition of the other four levels was adopted from [27]. At the operational level, how and what the aircraft will be used for during its operational life is defined. At the aircraft level, requirements, standards, and regulations are gathered to define aircraft functions and characteristics. This results in the generation of concepts of aircraft and its subsystems. At the subsystem level, subsystem concepts are generated and evaluated. Finally, at the component level, component concepts are generated and analyzed.

The liaising expert represented the product level in the workshop to represent the liaising role between the aircraft developer and the customer. The operational analysis expert and the overall aircraft design expert represented the operational and aircraft level, respectively. The subsystem level was represented by the ECS, fuel system, and sensor suite expert. The sensor suite expert represented all mission-critical systems of the aircraft. Finally, the component level was represented by the heat exchanger expert.

Each active participant was assigned a specific color. For example, orange was assigned to the liaising expert, green to the operational analysis expert as shown in Fig. 7. For the seven active participants, their designated color, workshop role, aircraft project design level, their past and current roles at Saab and external to Saab, and total number of years of experience are listed in Table 3.

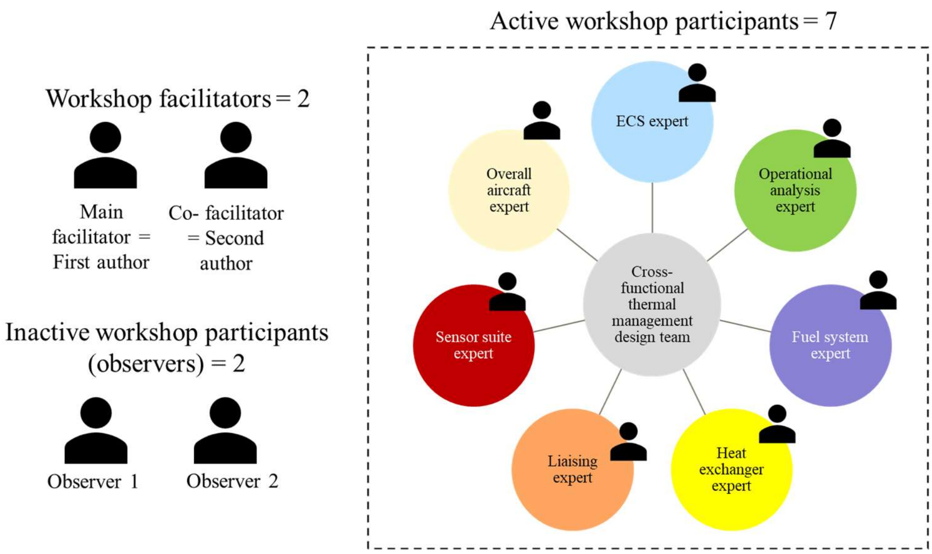
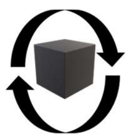
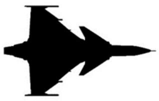
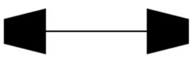


Fig. 7 The distribution and roles of the 11 workshop participants.

Table 3 The role, project design level, roles at Saab and external to Saab and total number of years of experience for each active workshop participant.

Active participant	**Aircraft project design level**	**Roles at Saab**	**Roles external to Saab**	**Total number of years of experience**
 Liaising expert	 Product	• Manager for Aero and Concept group • Technical Manager • Chief Engineer • Several other roles at Saab		34

Operational analysis expert	 Operational	• Test Pilot • Operational Analyst	• Pilot in Swedish Air Force	31
Overall aircraft design expert	 Aircraft	• Overall Aircraft Design Engineer • Airframe Design Engineer		38
ECS expert	 Subsystem	• Mechanical Design Engineer • System Design Engineer • System Technical Responsible	• Product Development Engineer	38
Fuel system expert	 Subsystem	• Stress Engineer • Structural Temperature Analyst • Fuel System Expert • PhD Student • Subsystem Concept Engineer		27
Sensor suite expert	 Subsystem	• System Engineer – Sensors • System Engineer – Simulators • Flight Test Engineer • Project Manager		20
Heat exchanger expert	 Turbine Compressor Component	• ECS Engineer • Secondary Power Engineer • Weapon System Engineer		12

	• System Safety Engineer

B. Workshop Execution Phase

1. Briefing Sessions Before Workshop

Individual in-person sessions were held by the first author with each workshop participant except the sensor suite expert one week prior to the start of the first workshop session. This was done to verbally brief them on the workshop goals and team. No written documentation was provided to them in this session. The sensor suite expert was briefed via email.

2. Overview of the Workshop Sessions

A total of three sessions were held with the team to meet the goals of the workshop. Each session was carried out with approximately two weeks between them. This provided the first and second authors with some time in between to process and analyze the data provided in each session. Each session was held in a conference room on site at Saab in Linköping, Sweden. All active participants were present in person for all three sessions except for the sensor suite expert who missed Session 3. His role was played by Observer 2 in Session 3. Observer 2 has 22 years of experience at Saab, of which four years were spent as a technical manager for tactical systems. The specific instructions and supporting documents for each of the three sessions were emailed to the workshop participants by the first author 24 hours before each session. Reminders, warnings, and general instructions that were common to all three sessions were also provided to them via email before Session 1. The general instructions and specific instructions for each session activity are listed in Fig. 8 . Across all three sessions, the active participants did not use calculators or any software to conduct the tasks. The numerical information provided in the pre-defined scenario simply served as a guide to help them with their tasks related to TM design. No session activities required them to do numerical calculations. For each session, a series of supporting documents were provided to each participant. These documents were provided to them in hard copy. A summary of these documents is listed in Fig. 9. The active participants did not work on computers during any sessions. Instead, they were provided with stationery to conduct their tasks. The list of stationery and other materials used in each session is summarized in Fig. 9.

General Instructions

- Please do not converse with the observers. It will introduce bias in the study. They are present in the capacity of observers.
- Please use block letters when filling out the cards or writing on sticky notes. Please avoid cursive writing. Please make sure your handwriting is legible

Workshop Session 1 Instructions

Activity 1: The individual TM design timelines

Step 1: In the context of thermal management design for the pre-defined scenario

- Discuss with other active participants and fill in the data/information card accordingly.
- Fill the cards based on how you currently work in Saab projects.
- Place cards on the concurrent engineering chart.

Activity 2: The cross-functional connection chart

Step 2: In the context of thermal management design for the pre-defined scenario

- Use your designated sticky notes to list all functional groups to be involved in a single step on the cross-functional connection chart.

Workshop Session 2 Instructions

Activity-based DSM

Step 1: Read Document 6 on design/dependency structure matrix (DSM)

Step 2: Study the pre-defined scenario in Document 2

Step 3: Study the 'Data entities for various design levels' document

Step 4: Discuss at your own leisure with fellow active participants

Step 5: With an empty DSM in front of you think about what data entities your entities provide to and depend on

Step 5: Participate in creating the DSM together

Workshop Session 3 Instructions

(Planned) Activity 1: The lean activity-based DSM

We will take the DSM we have created and try to cut out the excess 'weight' and make it a 'lean DSM'. There are only two rules to follow to create the lean DSM to remove the unnecessary 'x's.

- Rule 1: Only direct dependencies (No indirect dependencies!)
- Rule 2: The dependency must be in the context of thermal management.

Step 1: So, go through each of your data entities and see what they currently depend on. Ensure that the dependency follows rules 1 and 2. Otherwise remove that dependency.

Step 2: Discuss your dependencies with other active participants.

Step 3: We will fill in the 'lean DSM' together.

Activity 2: The common TM design timeline

Step 1: Read the pre-defined scenario in Document 2.

Step 2: Go over the 'data entities for various design levels' document.

Step 3: Refer to the lean DSM (on the TV screen).

Step 4: Discuss amongst yourselves (the seven active participants).

Step 5: Start placing data entity cards in the chronological order you deem appropriate for the requirements, objective functions, and pre-defined scenario (Document 2).

Step 6: Use the blue tack to temporarily stick the data entity cards on the timeline sheet.

Step 7: Use the blue tack and wool to demonstrate the iteration loops.

Step 8: We will fill in the timeline together (and position the cards in their spots with sticky tape permanently).

Step 9: Have a look at the common TM design timeline – now what do you want to change in the lean DSM?

Fig. 8 A list of general instructions common to all three workshop sessions and a list of instructions for activities in each of the three workshop sessions. TM is thermal management and DSM is design/dependency structure matrix.

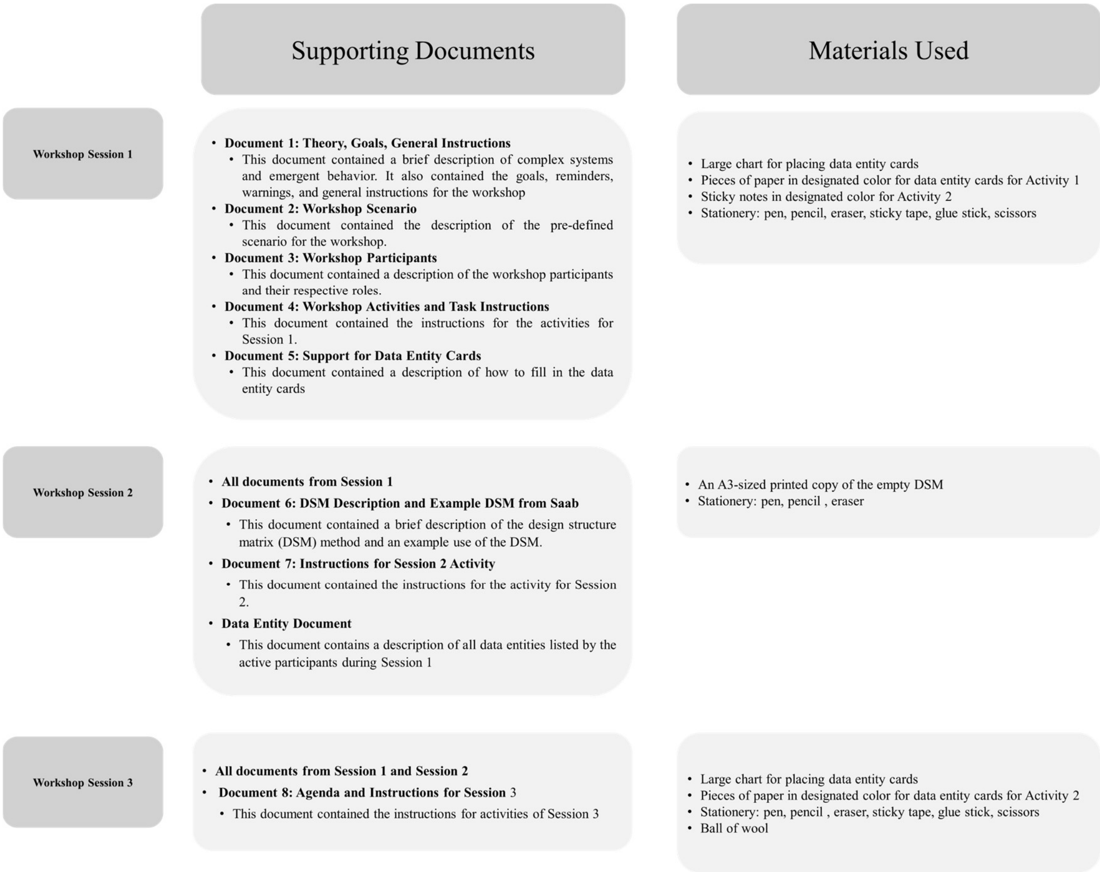


Fig. 9 A list of the supporting documents and materials provided to the participants for each workshop session. DSM is design/dependency structure matrix.

3. Workshop Session 1

Workshop Session 1 was two-hours long and consisted of two activities. The first activity required each active participant to create their individual TM design timeline on a concurrent engineering chart. One of the goals of the workshop was to create a common TM design timeline. However, firstly an individual timeline for each active participant was needed that consisted of the steps to be carried out by the individual expert in chronological order for TM design.

For the first half-hour of the session, the first author provided the participants with a brief description of theory on complex systems by [30] and emergent behavior by [28]. This was followed by an overview of the listed documents, activity instructions, and the stationaries available for use. For the next hour of the session, the participants read through documents 1 through 5 and then filled in their data entity (DE) step cards. Each card represented a step in an individual TM design timeline. When the DE step cards for an active participant were organized in chronological order on the concurrent engineering chart, they formed the individual TM design timeline for that participant. The participants used pieces of paper in their designated color as listed in Fig. 7 and Table 3 to fill out their DE cards. A DE step card had five entries to fill in. An example DE step card created by the first author as a demonstration to the participants is shown in Fig. 10. The first entry in the top left-hand corner of the card was the step number. In the example, in Fig. 10 it is designated 'S1' to represent the first step for the fuel system TM design timeline. The second entry was the DE itself. In this case it was the 'fuel tank wall thickness'. The third entry of the card was specifying the type of DE. The participants could choose from five different DE types. The list of these five DE types and a description and example of each type is shown in Table 4. The fourth entry was called 'Input From' and it entailed listing the functional groups that needed to provide information to the fuel system expert for this DE. And, finally the fifth entry on the card was called 'Impacts' and it entailed listing the functional groups that were impacted by this DE. Document 5 contained a description on how to fill in the DE step cards along with a list of the functional groups at

Saab Aeronautics for aircraft design. Each of the seven participants followed these instructions and created their individual TM design timelines. They presented the individual timelines in the last half hour of the session.

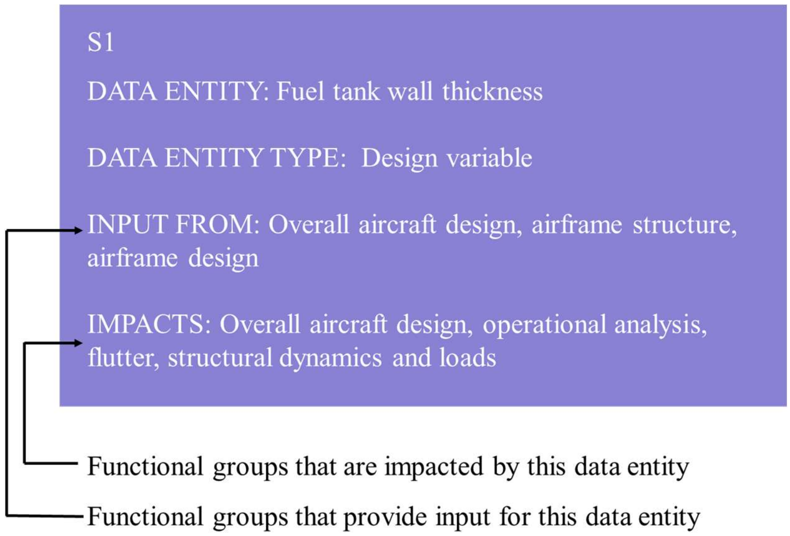


Fig. 10 The template for the data entity (DE) step cards that the seven active participants filled in for the first activity of Workshop Session 1. The template is filled out for the DE step S1 called fuel tank wall thickness.

Table 4 Descriptions and examples of the five data entity (DE) types the active participants could use when classifying their respective DE steps.

Data entity type	Description	Example
Design variable	An entity that the designer can vary	Type of material
System characteristic	An entity that is inherent to the system such as properties or performance of the system	Cost, weight of system
State variable	An internal variable	Pressure, temperature of system
Environmental variable	An entity that can varied in a computational model but not in real life	Atmospheric conditions such as temperature, humidity
Operational variable	An entity that can be changed by the operator after the system has been built	Duty cycle of the system

The second activity required the active participants to take the list of functional groups from the fourth and fifth entries for each DE step card and write them out on a sticky note in their designated color. The sticky note was then placed on the cross-functional connection chart. An example of such a sticky note on the cross-functional connection chart is shown in Fig. 11 and it was created by the first author as a demonstration for the participants using the DE example from Fig. 10. In a similar manner to the first activity of Session 1, the participants created a common cross-functional connection chart and presented their individual sticky notes to the rest of the group in the last half hour of the session.

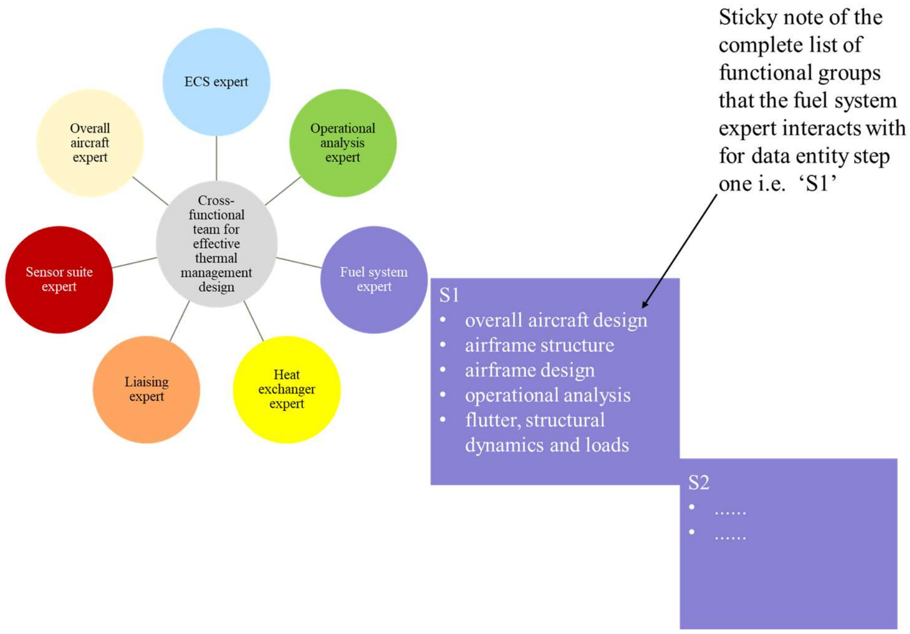


Fig. 11 A sticky note example created by the first author as a demonstration on the cross-functional connection chart that was filled out by the active participants for the second activity of Workshop Session 1. The example is the complete list of functional groups that the fuel system expert interacts with for the data entity (DE) step S1 described in Fig. 10. It would be followed by DE step S2.

4. Debriefing Sessions After Workshop Session 1

Member checking as noted in Ref. [31] is a means to investigate the credibility of the qualitative data collected from participants. Individual sessions with active participants were held with the first author after Workshop Session 1. In these sessions, the participants were asked to review the individual timelines they created on the concurrent engineering chart as well as the sticky notes they placed on the cross-functional connection chart. Therefore, these sessions provided the active participants with the opportunity to clarify their individual outcomes from the first workshop session with the first author.

5. Preparation for Workshop Session 2

Following the debriefing sessions, the concurrent engineering chart was digitized by the first author prior to the start of Workshop Session 2. This digitized chart was printed and provided to each workshop participant at the start of Session 2. This document was titled 'Data Entity Document' and it is listed under 'Supporting Documents' with 'Workshop Session 2' in Fig. 9.

6. Workshop Session 2

Workshop Session 2 was two hours long and consisted of a single activity. The activity required the active participants to work together to create an activity-based design/dependency structure matrix (DSM) using the Data Entity Document as a reference. The purpose of creating an activity-based DSM was to understand the dependencies between the DE steps of each individual timeline. Therefore, they had to list the dependencies between the various DE steps listed in the Data Entity Document. For the first half hour of the session, the first author provided the participants with a brief overview of the fundamentals of DSM as described by [32]. This was followed by an overview of the listed documents for the session, activity instructions, and stationaries available for use. For the next hour of the session the active participants started discussing the dependencies between their individual steps. They used their printed copies of the empty DSM to fill in their dependencies. In the last half hour of the session, the first and second author collated all the dependencies from the active participants in a single DSM in a Microsoft Excel sheet that was projected on a large screen in the conference room where the session was being held.

7. Workshop Session 3

Workshop Session 3 was three hours long and initially consisted of two planned activities. The session commenced with the first author providing a brief overview of the listed documents and activity instructions. The first activity was planned to provide the active participants with an opportunity to review the activity-based DSM they created in Session 2. They were asked to ensure that all dependencies were direct and in the context of TM design. However, they unanimously decided that they were satisfied with the DSM and did not want to amend it. Therefore, for the rest of the session, they focused on the second activity. Activity 2 entailed creating a common TM timeline for the DE steps for all seven active participants. The active participants referred to the Data Entity Document and the activity-based DSM to create this timeline. In Document 8, they were provided with a goal when creating the common TM design timeline. The goal was to meet the primary requirement and that was to ensure that the cooling power demands were met for Scenarios 1 and 2 as defined in Table 2. This means that the aircraft in the pre-defined scenario would have a high BVR capability and a TMS to support this capability. The secondary requirements entailed minimizing the aircraft signatures (IR and RCS), weight, and volume. The timeline was created on a large chart that was temporarily taped to a wall in the conference room where the session was being held. The participants used pieces of paper in their designated color to write down their DE step number and place it on the chart. After approximately an hour of discussion amongst themselves they presented the timeline to the workshop facilitators and observers. The first and second authors then clarified with the active participants that all DE steps were in the order they deemed correct.

C. Post Workshop Phase

1. Data Analysis and Derived Results

Following the completion of the workshop sessions, the results from the third session were digitized. The results from all three sessions were then analyzed by the first author and discussed with the other authors. From the analysis and discussion, a framework for effective thermal management design was created. In addition, the data provided in the cross-functional connection chart in Activity 2 of Workshop Session 1 were re-arranged. This chart also became part of the framework.

D. Minimizing Bias During the Workshop Execution Phase

Bias can arise during observation. Experimenter bias happens when the experimenter unintentionally communicates their expectations to the participants [33]. To minimize this bias, all information for each session was provided as described in Section IIA and Section IIB. The workshop facilitators did not partake in any discussions with active participants unless they wanted to clarify information provided in the documents. In addition, as noted under 'General Instructions' in Fig. 8, the active participants were asked to refrain from conversing with the workshop observers. Measurement artefact bias can happen when a software or measurement device does not fit the behavior of the participant [33]. The active workshop participants come from various functional groups across Saab and use different software to conduct their daily tasks. To minimize this type of bias, all activities required the use of only pen, paper, and other material as listed in Fig. 9.

III. Results and Discussion

The digitized results from the three workshop sessions are presented and discussed below. A framework for effective TM is also presented.

A. Workshop Session 1 – Activity 1 Outcome

The individual TM design timelines for the seven active participants are shown in Fig. 12, Fig. 13, and Fig. 14. The liaising expert had two data entities in his timeline that were both design variables. The first one, S1 entailed acquiring the initial dimensioning data for the weight, volume, and system configuration of the aircraft from the overall aircraft design group, initial missions from operational analysis, and sensor usage from the sensor system groups. The second entity entailed the cooling power budget for all consumers. Therefore, the liaising expert acquires and distributes information. The operational analysis expert had six data entities which were system characteristics of the aircraft such as allowed envelope, range, signatures, and usage of sensors such as radar and electronic warfare. The envelope in this case refers to the Mach number and altitude envelope. All these entities were to be acquired by the operational analysis expert by interacting with various functional groups. S2 for example would be acquired by interacting with several functional groups. The overall aircraft design expert had eight data entities which were either design or operational variables. To determine his variables, he also needs to interact with several functional groups especially for his first entity, S1. He is also responsible for determining the primary parameters of the terminal heat sinks such as mass flow rate of ram air and fuel. The ECS expert had eight data entities which were either system characteristics or design variables. He acquires the cooling power requirements and heat sink usage from overall aircraft design. All his data entities either require input from or they impact overall aircraft design. The fuel system expert had seven data entities which were system characteristics, operational variables or state variables. His data entities require input from overall aircraft design or from interface documents, especially those with the engine. His S1 and S2 are very similar to S3 and S2, respectively of the ECS expert. This is understandable since the fuel system functions as a terminal heat sink and is part of the TMS as shown in Fig. 4. The sensor suite expert only had two data entities and both were design variables. The first entity S1 pertains to acquiring budgets for volume, weight, position of the sensors from overall aircraft design, operational analysis, aircraft survivability, and electrical power system. These budgets impact the sensor system performance. The second entity S2 pertains to acquiring some sensors positions from the ECS expert. This is because some sensors have high cooling power demands (kW). The optimal positions of these sensors are driven by the cooling fluid pipe routing from the ECS to the sensors in the airframe. Finally, the heat exchanger expert had three data entities of which S1 is a system characteristic and S2 and S3 are operational variables. All three data entities require input from overall aircraft design, ECS, and fuel system and they impact these functional groups as well. S1 impacts airframe design, too. The seven individual timelines consisting of the respective DE steps served as a reference for the activities that followed on in Sessions 1, 2, and 3.

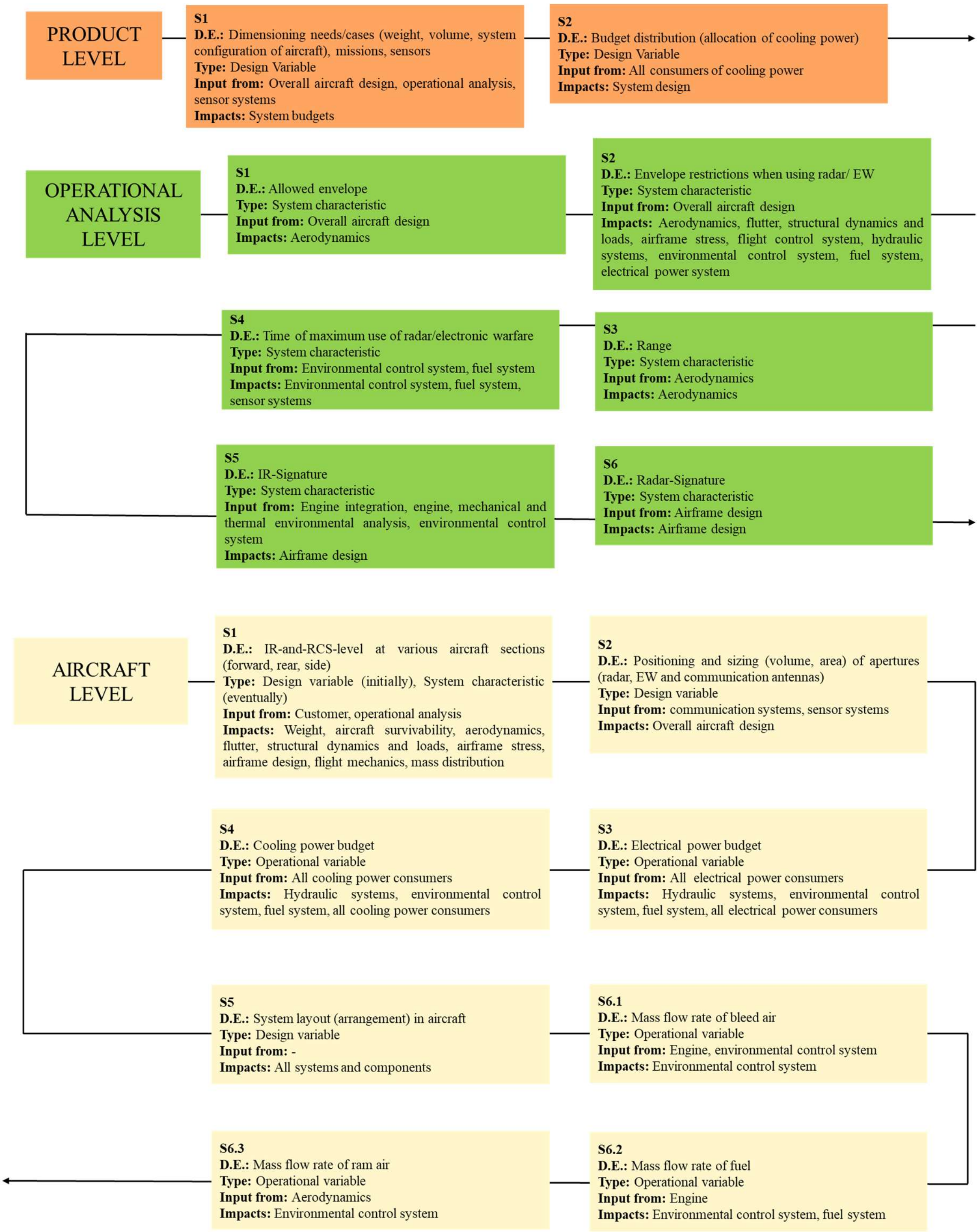


Fig. 12 The individual thermal management design timelines for the liaising expert at the product level, the operational analysis expert at the operational level, and the overall aircraft design expert at the aircraft level. Each individual timeline consists of the data entity steps labelled S1, S2, and so on in chronological order. IR and RCS are infrared and radar-cross section, respectively. EW is electronic warfare.

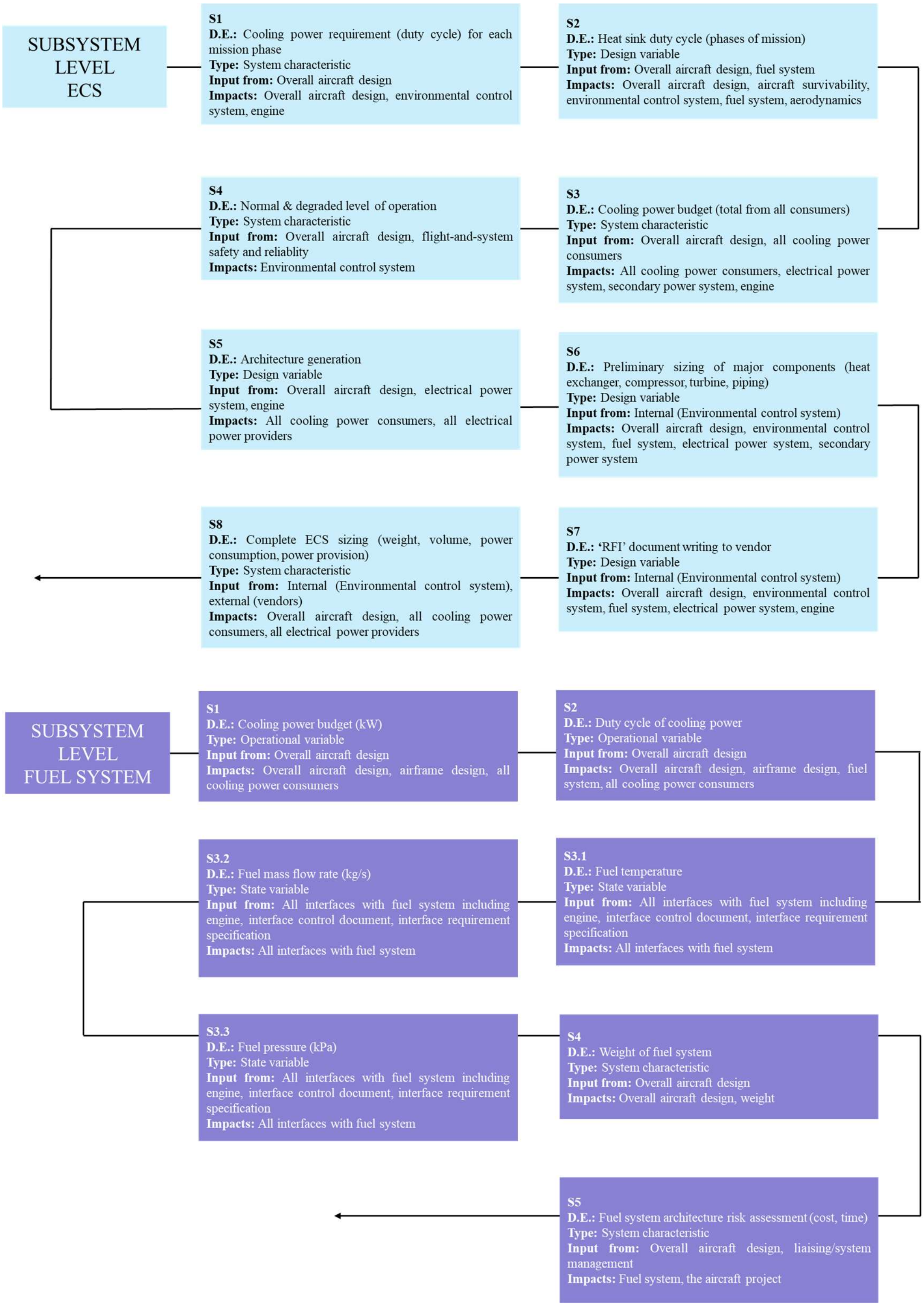


Fig. 13 The individual thermal management design timelines for the environmental control system (ECS) expert and the fuel system expert at the subsystem level. Each individual timeline consists of the data entity steps labelled S1, S2, and so on in chronological order. RFI is request for information.

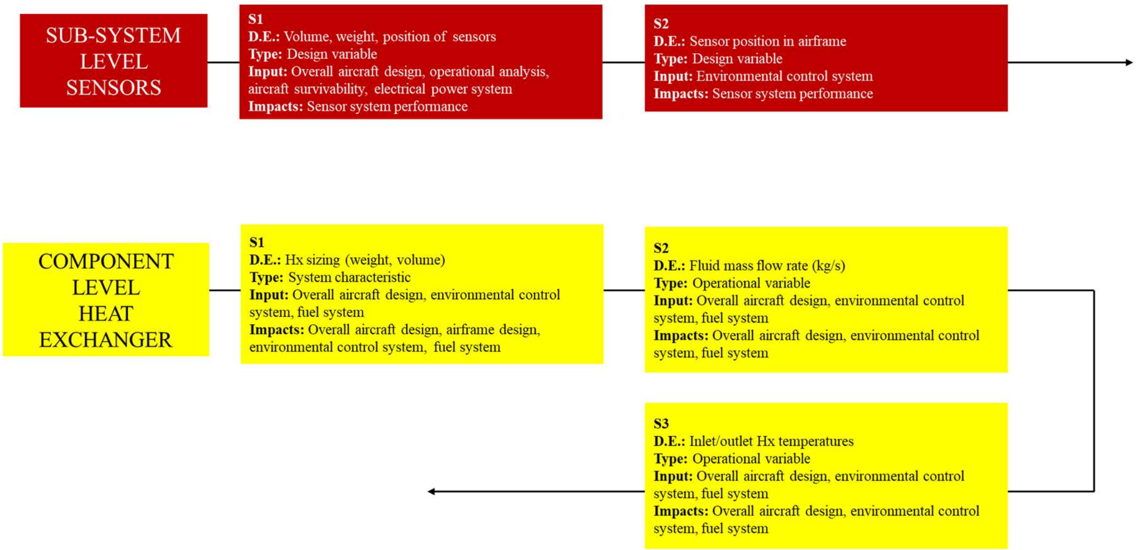


Fig. 14 The individual thermal management design timelines for the sensor suite expert at the subsystem level and the heat exchanger expert at the component level. Each individual timeline consists of the data entity steps labelled S1, S2, etc. in chronological order. Hx stands for heat exchanger.

B. Workshop Session 1 – Activity 2 Outcome

The workshop outcomes demonstrated how highly interactive the seven active participants need to be not only within the TM design team but with other functional groups as well. In Activity 2 of Session 1, the active participants created a cross-functional connection chart listing all functional groups needed for each of their respective DE steps. An example of this was shown in Fig. 11. The chart consisted of all the functional groups that provide input to or are impacted by each DE step for each active participant. The data in the chart were re-arranged to cluster all the DE steps that need to interact with a specific functional group. This is shown in Fig. 15. For example, operational analysis for S1, S2, and S3, overall aircraft design for S1 and S6.3, and ECS for S2 interact with the functional group 'Aerodynamics'. It can be clearly noted that the overall aircraft design expert at the aircraft level interacts with the greatest number of DE steps. This is expected given that at the aircraft level all information for defining aircraft functions and characteristics is gathered. Therefore, Fig. 15 provides a visual overview of the cross-functional interactions needed for effective TM design at the aircraft concept stage.

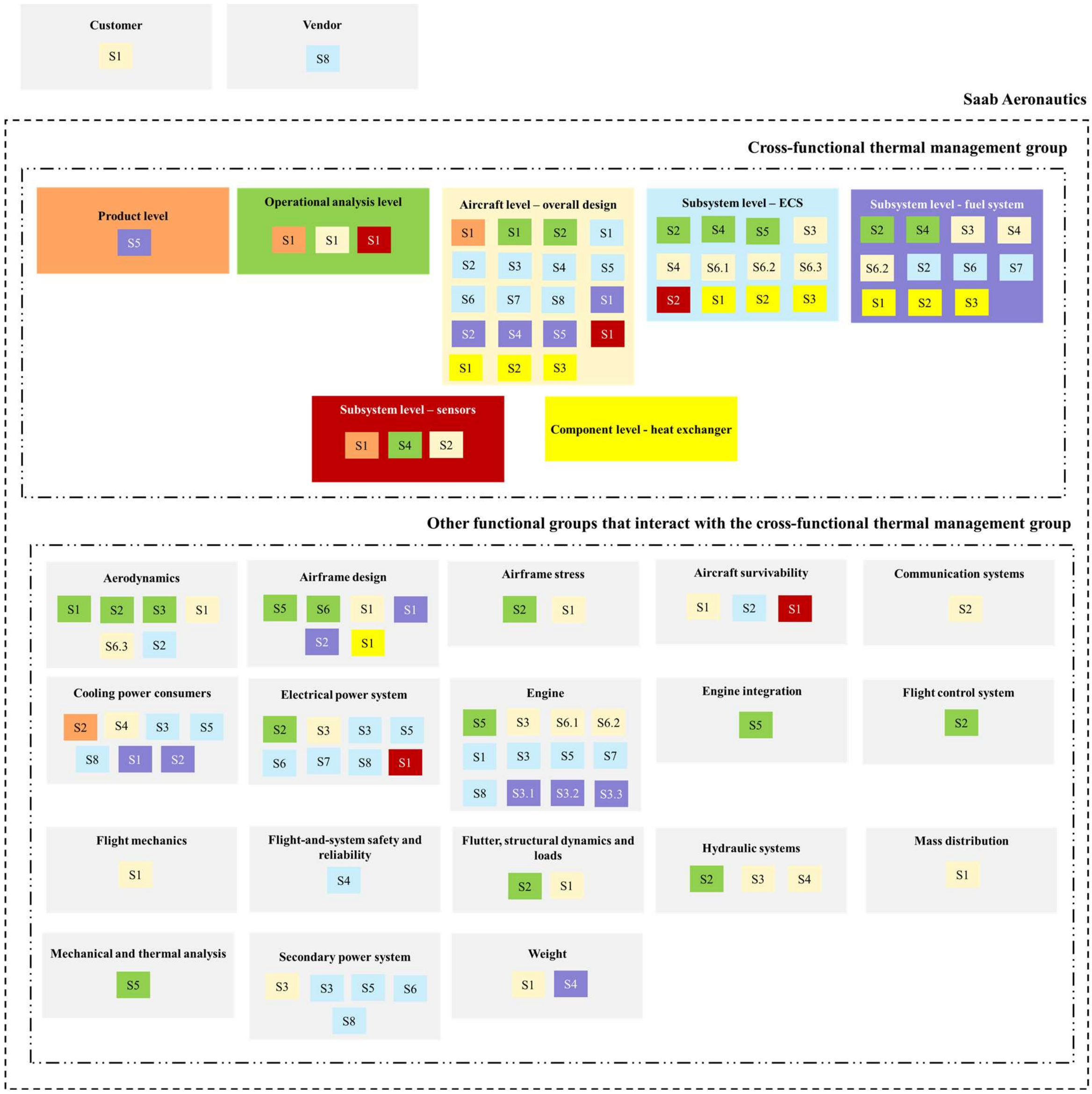


Fig. 15 The cross-functional connection chart to support effective thermal management design. This chart was created by re-ordering the data in the cross-functional connection chart created by the seven active workshop participants for Activity 2 of Session 1. The chart consists of all the functional groups that provide input to or are impacted by each data entity (DE) step for each active participant. S1, S2, etc. represent the DE steps for each of the seven active participant in their designated color defined in Fig. 7. ECS is environmental control system.

C. Workshop Session 2 – Outcome

The activity-based DSM created by the seven active participants to determine the dependencies between their respective DE steps is shown in Fig. 16. Going across the first row of the DSM, orange S1 i.e. S1 for the product level provides to orange S2, green S1 through S6, lemon S1, red S1 and S2, and blue S1 to S4. Therefore, S1 at the product level provides to the largest number of DE steps in the DSM with a total of 14. This is because it entails the initial dimensioning information from overall aircraft design and operational analysis. All the DE steps of operational analysis depend on S1 and S2 of the product level since those system characteristics would depend on initial dimensioning and budget distributions. The DE steps of operational analysis provide to various steps at different design levels. S1 of operational analysis, i.e. allowed envelope provides to determining the IR-and-RCS-level for overall aircraft design. Since airframe skin temperature is impacted by Mach number and altitude and it can significantly impact the IR signature of the aircraft. The allowed envelope also impacts the sensor performance, and this provides to the data entities of the sensor suite expert. When flying at low altitude and high speed, the fuel system would not be an effective terminal heat sink. Therefore, the cooling power budget for the fuel system is also impacted by the allowed envelope in terms of Mach number and altitude. Similarly, the mass flow rate of ram air to the heat exchanger and inlet and outlet temperatures of the heat exchangers would be impacted by where in the envelop the aircraft is operating. Some DE steps for ECS and heat exchanger are dependent on nearly all data entities of overall aircraft design. ECS S8 (complete ECS sizing in terms of weight, volume, power consumption and provision) depends on all DE steps of overall aircraft design. Similarly, S2 and S3 for the heat exchanger depend on all data entities but S2 of overall aircraft design. This is because overall aircraft design is responsible for power budgeting and mass flow rates of terminal heat sink fluids. Therefore, this activity-based DSM shows the dependencies between all the DE steps of the seven active participants. It is needed to conduct TM design effectively within a cross-functional team.

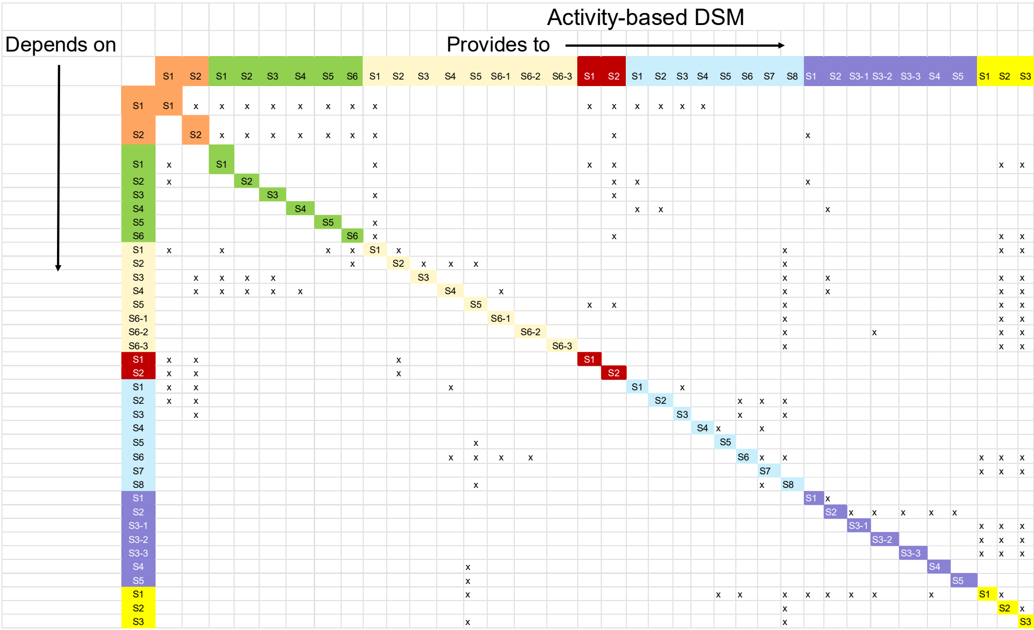


Fig. 16 The activity-based design/dependency structure matrix (DSM) displaying dependencies between the data entity steps labelled S1, S2, etc. for each of the seven active workshop participants in their designated color defined in Fig. 7. An example to read the DSM would be to go across the first row of the DSM where orange S1 provides to orange S2, green S1 through S6, lemon S1, red S1 and S2, and blue S1 to S4.

D. Workshop Session 3 – Outcome

The common TM design timeline created by the seven active participants is shown in Fig. 17. The timeline represents the chronological or sequential ordering of the DE steps. DE steps that are parallel with one another can be determined concurrently. The dashed arrows represent iterative loops between DE steps. Prior to creating the timeline, the active participants unanimously decided that the timeline would be the same regardless of the primary and secondary requirements on the fighter aircraft. Therefore, they deemed a common TM design timeline would be independent of the aircraft capability requirements. Also, before creating the timeline, the liaising expert split his first DE step S1 into S1.1 and S1.2, where S.1.1 represents what the customer needs from the product and S1.2 represents the original S1 as defined in Fig. 12. The timeline commences with the customer needs, followed by allowed envelope and then dimensioning needs/cases. The ECS expert commences with his steps after budget distribution by the liaising expert is determined. Following the initial sizing of the major components, the heat exchanger expert commences with all his three steps simultaneously. These three steps are in an iterative loop with initial sizing. The fuel system expert commences with his first step, S1 after the budgets from overall aircraft design (S3, S4) are available. Heat exchangers steps are determined for a second time following the availability of fuel mass flow rate, temperature, and pressure and assuming vendors have responded to the requests for information. Again, the heat exchanger steps are looped back to

ECS major component sizing. Following the finalizing of the ECS architecture and complete ECS sizing, S2, S3, and S4 for operational analysis can be determined. The restrictions on the envelope and the maximum use of the radar and electronic warfare are determined by the maximum cooling power provided by the ECS to these sensors. S2, S3, and S4 loop back to the S1.2 of the liaising expert to determine if the needs are met. This demonstrates how operational capabilities are dependent on the performance of a basic aircraft function such as TM. Therefore, the timeline can be used to conduct TM design iteratively at the aircraft concept stage.

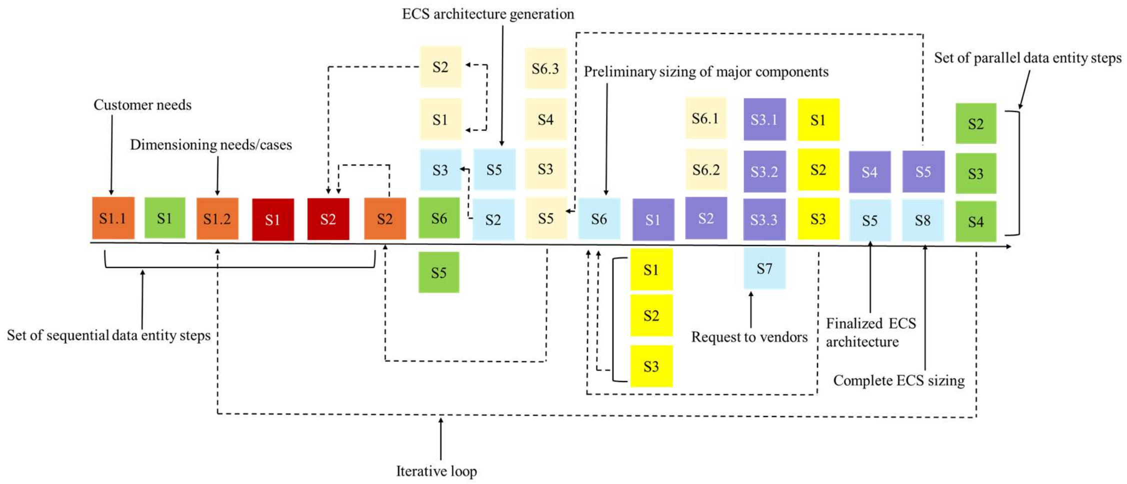


Fig. 17 The common thermal management design timeline for the data entity steps labelled S1, S2, etc. for each of the seven active workshop participants in their designated color defined in Fig. 7. ECS is environmental control system.

E. A Framework for Effective TM Design

Data collected for the pre-defined scenario and the outcomes from the three workshop sessions resulted in a summary of the common TM design timeline at the aircraft concept stage. It is presented in Fig. 18.

The first stage of the summary entails three steps 1.1, 1.2, and 1.3 that can be conducted simultaneously. Determining the worst operating conditions for TM and the physical design aspects related to aircraft capabilities that impact TM design can be done in a similar way as shown in Fig. 3, Table 1, and Table 2. Dimensioning on an aircraft level for weight, volume, and power (kW) requirements can be done as described by S1 at the product level and S3, S4, and S5 at the overall aircraft design level shown in Fig. 12. When this information is available, the ECS architectures can be generated. Simultaneously, the parameters of all available heat sinks in the aircraft can be determined. This would include the mass flow rate, inlet temperature and pressure of the heat sink fluids. Note that this step is in contradiction with the sequential arrangement in Fig. 17. The common TM timeline has S6 of the ECS precede S6.2 of overall aircraft design. Instead, the authors propose that preliminary sizing of major ECS components proceed after the mass flow rate of fuel is determined. Therefore, when the parameters of all available heat sinks are known, the preliminary sizing of major components can be done. This is so that the most effective terminal heat sink can be coupled to the heat exchangers for worst operating conditions. The fourth stage entails ECS component scouting. While S7 of the ECS only focuses on writing RFIs to vendors, in this framework technology scouting is considered in a broader context. Aside from state-of-the-art commercial off the shelf equipment from vendors, technology scouting can also entail the aircraft developer look within the organization for technologies in existing aircraft. It could also include the organization developing their own technologies for a specific aircraft project in collaboration with vendors. When the major components are decided on, the ECS architecture can be finalized in the fifth stage followed by the complete sizing of the ECS in the sixth stage. Stage 5 and 6 can be carried out in a similar manner to S5 and S8 of the ECS, respectively as shown in Fig. 13. The sizing of the ECS entails determining its maximum cooling capacity for the cooling power demand in the worst operating conditions. This determines the restrictions in the envelope and the length of use of sensors in these conditions. Therefore, in the final stage if the cooling capacity falls below the required demand, then a second iteration commences at the second stage (2.1 and 2.2 in Fig. 18). In this study, to meet the primary requirement of the cooling power demand to support the high BVR capability of the aircraft, the secondary requirements may be compromised. Therefore, either the ram air cross-sectional inlet and outlet areas are increased or larger heat exchangers are used. The first option would result in an increase in the mass flow rate of ram air that in turn would increase the heat sink capability of the TMS and therefore the cooling capacity of the ECS. However, it could also result in an increase in the IR and RCS signatures due to the larger inlet and outlet areas. The second option could result in an increase in the cooling capacity of the ECS however the volume and possibly weight of the ECS would increase and that would add to the total volume and weight of the aircraft. Referring to Table 1 that listed the physical design aspects related to aircraft capabilities that impact TM design, stealth or maneuverability and agility or both may be compromised so the TMS can support the high BVR capability of the aircraft. Therefore, the summary of steps can be used to iterate TM design at the aircraft concept stage and understand the implications on aircraft and operational capabilities.

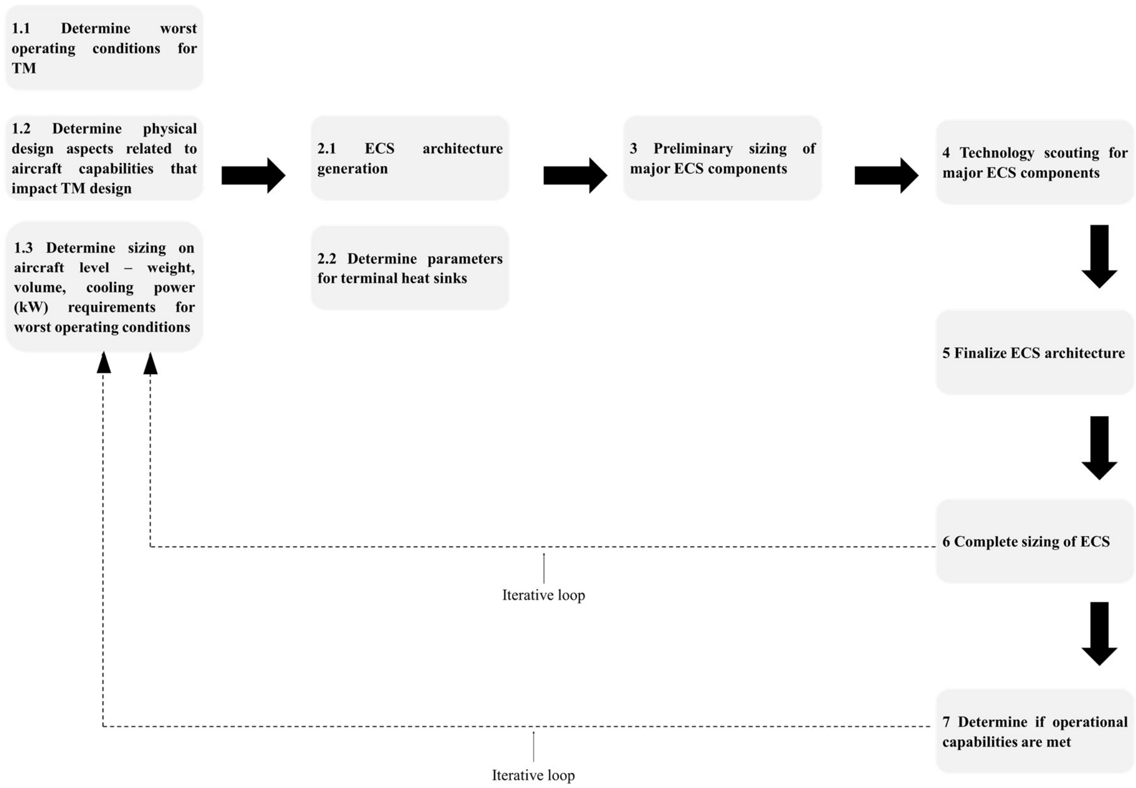


Fig. 18 A summary of the common thermal management design timeline at the aircraft concept stage. ECS is environmental control system.

This summary for TM design is similar to Figure 2 of Ref. [24]. However, the summary in this paper is complemented by the detailed common TM timeline in Fig. 17, the individual TM timelines, the activity-based DSM, and the cross-functional connection chart. Together they all result in a framework for effective TM design at the aircraft concept stage. The individual timelines on the concurrent engineering chart provides a chronological and detailed outline of the steps each functional group involved in the core TM design team needs to carry out. The activity-based DSM provides the dependencies between the various steps of the individual timeline. The common TM design timeline provides the detailed chronological order for the single and complete process for TM design. Finally, the cross-functional connection chart demonstrates all the interactions that need to take place within the TM cross-functional team and the interactions with other functional groups external to the team. The ECS and fuel system architecture presented in this study can be used as a case study to test the framework. The framework can be used to determine if they can support the cooling power (kW) requirements for the 2030 and 2040 scenarios listed in Table 2 for the mission profile presented in Fig. 3. The framework presented can complement the methods for TM presented in Refs. 7- 9, 11, 12, 14, 16, 19, 21-25. The framework provides the order in which the information is available in, the dependencies between the information, and the functional groups at an aircraft developer that need to be involved to obtain it.

IV. Conclusions

A cross-functional workshop as a methodology is presented in this paper to understand how TM design can be conducted effectively at the aircraft concept stage. The workshop consisted of three parts: the set-up phase to define a scenario for TM design, an execution phase to run the workshop sessions, and a post-workshop phase to analyze the data from the sessions. The workshop resulted in a framework that can be used to conduct effective TM design at the concept stage at an aircraft developer like Saab. The framework presents a detailed understanding of the steps to be carried out iteratively for TM design by a cross-functional team. It also provides the dependencies for these steps and the various functional groups that need to be involved in each step. The steps can be used to iterate TM design at the aircraft concept stage and understand the implications on aircraft and operational capabilities. The framework can complement other methods presented in literature for aircraft TMS architecture generation and TM modelling and simulation. Finally, the workshop methodology can be used to obtain similar frameworks for design of other basic functions at the aircraft concept stage.

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