Digitalization of Space Thermal Engineering

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Digitalization has been a hot topic across all industrial sectors for a number for years now. Within ESA there have been a number of R&D activities initiated on the topic together with industrial partners. The purpose of this paper is to present the digitalization topic to a wider audience, and with a specific focus on the thermal engineering and its related interfaces. Generally digitalization refers to improving engineering activities by using digital technologies; for example to make processes more efficient, or to enable richer data sources to be exploited. Therefore a necessary precursor for digitalization is the "digitization" of engineering data into machine interpretable assets (e.g. transforming from a document centric to a model centric approach). This paper will present an analysis of the space thermal engineering process, identifying the input and output data of the different thermal engineering tasks. The way to capture and describe this data using formal ontologies as well as open standards will also be discussed. Some concrete examples of digitalization, including R&D activities ongoing at ESA, will be presented, specifically related to core thermal engineering tasks such as thermal testing and operations. The context for space thermal engineering software tools will also be discussed, for example, the needs for interfaces to author and consume metadata, such as design information, and test/flight data.

Nomenclature

AIT/V	=	Assembly, Integration and Test or Verification
ESA	=	The European Space Agency
ESTEC	=	European Space Research and Technology Centre
FEM	=	Finite Element Model
GMM	=	Geometric Mathematical Model
JSON	=	JavaScript Object Notation
PLM	=	Product Lifecycle Management
MBSE	=	Model Based Systems Engineering
RF	=	Radio Frequency
R&D	=	Research and Development
SDM	=	Simulation Data Management
STEP-TAS	=	STandard for the Exchange of Product model data - Thermal Analysis for Space
TMM	=	Thermal Mathematical Model
UML	=	Unified Modeling Language
VISTA3D	=	Visualization of Spacecraft Telemetry and Acquisitions in 3D

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I. Introduction

A. Digitalization in the context of space thermal engineering

Digitalization is a hot topic across the space sector and many R&D activities are ongoing across industry, including a number of ESA funded activities[1-4]. The ESA Agenda 2025 white paper[5] puts digital transformation as a key priority stating: "*ESA will digitalize its full project management, enabling the development of digital twins, both for engineering by using Model Based System Engineering, and for procurement and finance, achieving full digital continuity with industry*."

It is important that all of the engineering disciplines, together with system engineering teams and data systems specialists, take active steps to enable the digitalization of their process. In the field of space thermal engineering, the community that makes up the ICES session *"Thermal and Environmental Control Engineering Analysis and Software"* is well placed to take an active and leading role in the digital transformation, due to the relevant competencies in software engineering. Furthermore, it is expected that the analysis tools will need to interact closely with the new digital systems. They are expected to consume data from these systems and also provide user friendly and feature rich authoring tools to support thermal engineers to populate the systems.

It is important to describe here what is actually meant by *digitalization*. In this paper, the term *digitization* is used to refer to the conversion of analogue media into a digital representation. As such the scanning of a paper document into a PDF file is a *digitization* activity. However, this term is not particularly useful, and the translation of legacy analogue assets into digital files is not a driving motivation. Therefore it is useful to extend this idea of *digitization* to also include the transformation of existing (digital) documents, such as Word files or presentations, into *machine interpretable* digital assets, and indeed this is one of the core goals of the Model Based Systems Engineering (MBSE) movement. Conversely *digitalization* refers to the transformation of an organization's processes and activities to fully exploit digital technologies and the digital assets.

An example of digitization in the space thermal engineering domain could be the digitization of test instrumentation plans, which today are often an annotated set of images in a PDF document. A true digital representation, however, might link for example the physical location of sensors (exploitable from CAD, or analysis), degrees of freedom of mathematical models (FEM and thermal nodes), and other media (photographs, calibration records, etc.). However, in order to fully exploit these digital assets, the processes of the engineering teams need to be changed, for example to a digital authoring of the instrumentation plan, rather than using plain office automation tools. Moreover AIT/V teams need to be able to rapidly and efficiently access this information during installation of hardware, with the possibility to update records to reflect the current as-built state, possible supported by emerging extended reality systems[12].

B. Opportunities for digitalization in the space thermal engineering domain

When prioritizing activities for digitalization there are two ways to proceed: top-down and bottom-up. For example, in the top-down approach engineers are consulted about where their greatest process inefficiencies lie, and then ways in which digitalization can be used to address these inefficiencies are sought. Conversely, in the bottom-up approach, a full audit of current processes can be carried out and the individual data sources that are to be digitalized can be identified. In *Section III s*ome examples of a bottom-up analysis of the processes are presented, however, it is also useful to consider at a high level some of the opportunities for digitalization to support thermal engineering processes. Some of these opportunities are outlined below:

- to improve process efficiency and reduce cost
- to reduce errors and increase robustness of data
- to facilitate the exchange of information with third parties (i.e. primes, sub-contractors, and other disciplines)
- to provide traceability and configuration control to data
- to enable other activities e.g. digital twin, use of Artificial Intelligence, etc.

Before attempting to identify and describe these processes specific to space thermal engineering, existing open standards should be reviewed to see how they may fit within the digitalized landscape.

II. Open standards

A. Challenges

One of the main challenges around digitalization is how to gain adoption throughout industry, and other stakeholders. The end user will not gain anything from digitalization if the population and administration of data models is a complicated and/or time-consuming task that comes in addition to the day-to-day work. Rather the tools and data systems need to evolve so that the interfaces with the new data models are embedded in the processes with efficient and user friendly interfaces.

The challenge here is that different organizations are using different engineering tools and, to some extent, different processes. In the context of thermal engineering this might mean different material property databases, different thermal analysis tools, different CAD platforms, as well as product lifecycle management (PLM) and simulation data management (SDM) platforms. One way to address this is to try and use open standards to support digitalization and some reflections on this are given in the following sections.

B. The ECSS glossary of terms

The European Cooperation for Space Standardisation (ECSS) is a European organization made up of national agencies, industry and ESA. Its primary task is: *"to develop a common set of consistent standards for hardware, software, information, and activities to be applied in space projects."* In the context of digitalization it is useful to highlight that the ECSS glossary of terms[6] already contains a wealth of definitions that are in common use in the space industry and endorsed by the European community. Especially when different stakeholders are working on digitalization and a number of different initiatives and studies are underway, it is essential to try and align terminology as much as possible in order to guarantee semantic interoperability between data models. The ECSS glossary of terms is considered to be a useful input to achieve this objective.

C. The STEP-TAS Standard

The STEP-TAS standard is a standard for the exchange of thermal analysis data. The protocol underpinning the standard is described in the ECSS standard[7] and a previous ICES paper[8] describes the standard in more general terms (although some of the perspectives from this paper are out of date).

The STEP-TAS standard is most commonly used for the exchange of Geometrical and Thermal Mathematical models (GMM/TMMs), however, much more than this is actually possible, including space mission and kinematics aspects, and a generic mechanism for representing *"results"* data. In many ways the term *"results"* is unfortunate and misleading, as in fact this mechanism can be used to store test data, flight data, or, as will be shown here, other data sets such as requirements. Indeed the STEP-TAS protocol already anticipates this as can be seen in section 1.3.2 of the protocol[9].

The storage of results data (analysis results, test data, flight telemetry etc.) with STEP-TAS is based around the concept of a data cube with three axes:

1. **items**
   where in the model does this property apply (e.g. which thermal node, temperature reference point etc.)
2. **quantity types**
   what is the type for which a property is stored in the dataset (e.g. temperature, capacitance, etc.)
3. **states**
   when a property is observed (e.g. time, frequency, or system mode)

To demonstrate how the STEP-TAS standard could be used to support digitalization, the example of thermal requirements definition can be considered which is presented graphically in Figure 1. To describe thermal requirements data in a machine readable way using existing technology and terminology, the ECSS terminology can be combined with a STEP-TAS data model to represent it. In Table 1, a number of definitions are proposed based on ECSS vocabulary, with mappings to STEP-TAS data types.

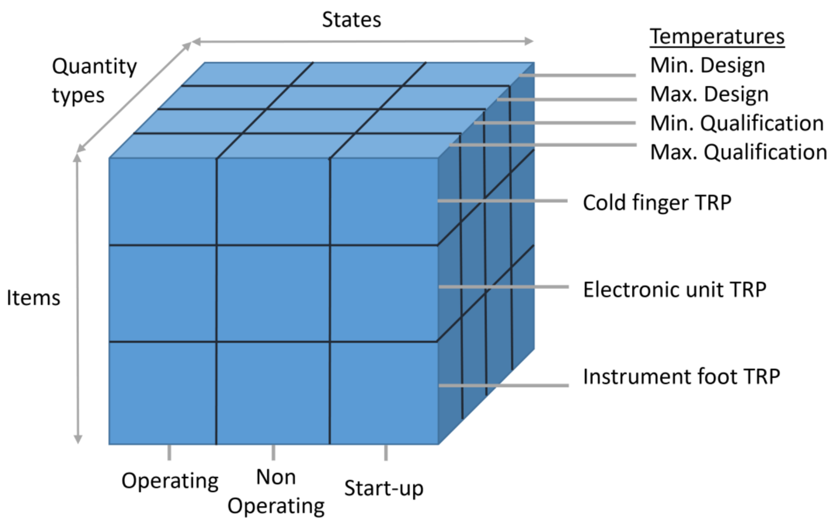

Figure 1. Example of a STEP-TAS datacube to describe temperature requirements for TRPs

ECSS term	Data cube axis	STEP-TAS data type	Possible STEP-TAS state name
Minimum Acceptance temperature range	quantity type	nrf_qualified_physical_quantity_category	`ecss_e_31_minimum_acceptance_temperature`
Maximum Acceptance temperature range	quantity type	nrf_qualified_physical_quantity_category	`ecss_e_31_maximum_acceptance_temperature`
Minimum Qualification temperature range	quantity type	nrf_qualified_physical_quantity_category	`ecss_e_31_minimum_qualification_temperature`
Maximum Qualification temperature range	quantity type	nrf_qualified_physical_quantity_category	`ecss_e_31_maximum_qualification_temperature`
Minimum switch-on temperature	quantity type	nrf_qualified_physical_quantity_category	`ecss_e_31_minimum_switch_on_temperature`
Temperature reference point	item	nrf_named_observable_item_class	`ecss_e_31_temperature_reference_point`
System interface temperature point	item	nrf_named_observable_item_class	`ecss_e_31_system_interface_temperature_point`
Operating	state	nrf_string_quantity_type	`ecss_e_20_operating`
Not operating	state	nrf_string_quantity_type	`ecss_e_20_not_operating`

Table 1. Mapping of ECSS definitions to STEP-TAS data types to describe thermal requirements

Table 1 is by no means exhaustive and other concepts and vocabulary could readily be mapped to STEP-TAS, for example dealing with thermal modelling uncertainty. However, it can be seen that the three axes of a data cube can be mapped to existing terminology and a data cube can be populated to describe temperature requirements. Clearly this concept can be extended to describe power dissipation instead, however, more mission specific states might be needed to describe system modes.

This section is not intended to actually propose that STEP-TAS is a complete standard that can be used for digitalization. Rather the purpose is to show that, by using *existing* standards and tools, some common thermal engineering data can be moved out of spreadsheets and documents and into a machine interpretable format. A critical review of open standards is seen as an important step before starting to digitalize thermal engineering processes, in particular the terminology is expected to contribute to the development of ontologies.

II. Approach to thermal process digitalization

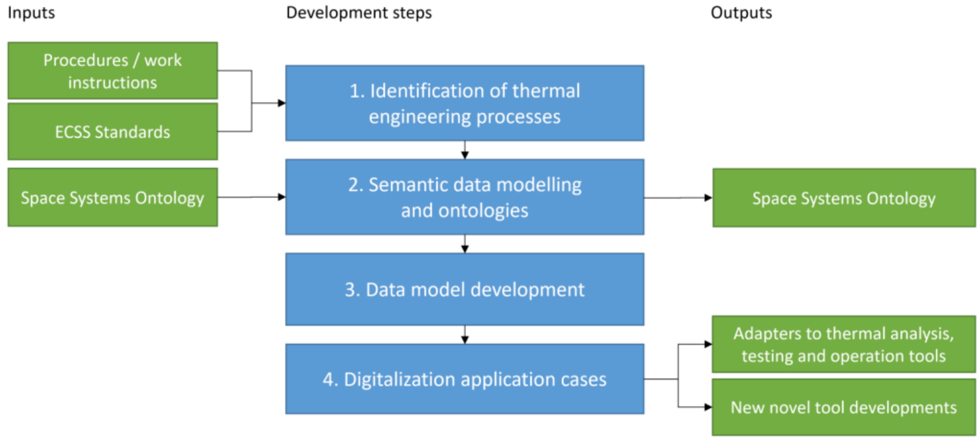

Figure 2: Key steps to digitalize space thermal engineering processes

Figure 2 describes an approach to the digitalization of thermal engineering processes. The approach consists of a number of steps for which some dedicated examples are further presented in this paper:

1. **Identification of thermal engineering processes**
   Following the bottom-up approach, the first step requires input primarily from thermal engineers to determine processes to digitalize. The processes are listed together with input and output data, data formats, and any associated schemas. In addition, it is necessary to critically review existing procedures and open standards (i.e. ECSS) for terminology. Dedicated examples of process descriptions for thermal design and heater line sizing are presented in *Section III(A)*.

2. **Semantic data modelling and ontologies**
   This step is associated with the semantic data modelling of the data identified from the processes in step #1. A semantic data modelling language may be used to describe facts and relationships between data. Specific vocabulary is defined and used to build ontologies which are harmonized with the community e.g. the Space Systems Ontology (OSMoSE)[2]. *Section III(B)* introduces the modelling of a spacecraft panel from a thermal perspective and *Section IV(A)* presents a conceptual data model of a thermo-elastic data pack delivery.

3. **Data model development**
   From the conceptual data model and ontology in step #2, the data model is mapped to a database structure (e.g. unstructured, relational tables, or object oriented), often referred to as *logical* and *physical* data modelling. At this stage a suitable database technology can be selected to be used to store and access the data model.

4. **Digitalization application cases**
   One of the key benefits of digitalization, is the possibility to exploit the data model in application use cases, e.g. model authoring, review package preparation, or analysis tools. Adapters to existing thermal analysis, testing or operations tools may be needed to interface with the data model. New novel tools may be more quickly developed and have a larger chance for adoption across industry as a result of standardized interfaces with the data model. Two application cases are elaborated in *Section IV* to produce thermal data driven views on testing and spacecraft operations.

III. Identification of thermal engineering processes

A. Describing processes

One of the initial steps in the digitalization of thermal engineering is to describe current processes. The main objective of this work is to sort the tasks to be performed at different project stages, taking into account their order of execution. Then, to determine the data flow during the project, the associated input and output data is listed for each process. Examples of associated data may not be limited exclusively to numerical data, but may include models and richer data sources. Next, the interfaces between process are identified, including those to processes with interactions to other stakeholders, for example to other disciplines such as the spacecraft electrical sub-system. This step attempts to detect potential bottlenecks in the data flow in a project. For example, the design of the electrical architecture must be available before the process for heating line sizing can begin.

Figure 3 presents a first iteration of process descriptions for several project stages, including examples of thermal engineering processes from requirement definition to thermal testing. The following steps are highlighted:

- **Design hardware management**
  The thermal engineer specifies and supervises thermal hardware solutions and monitors thermal aspects of subsystems during the spacecraft development (Figure 3 - Step 3).
- **Design simulation management**
  The thermal engineer verifies the thermal performance of the selected hardware by performing simulations and comparing predictions against requirements (Figure 3 - Step 3).
- **Tests management**
  The thermal engineer prepares the test campaign and checks and correlates hardware performance to models. It is interesting to note that at this step that processes become more sequential and each process depends on fewer data inputs from other disciplines (Figure 3 - Step 4).

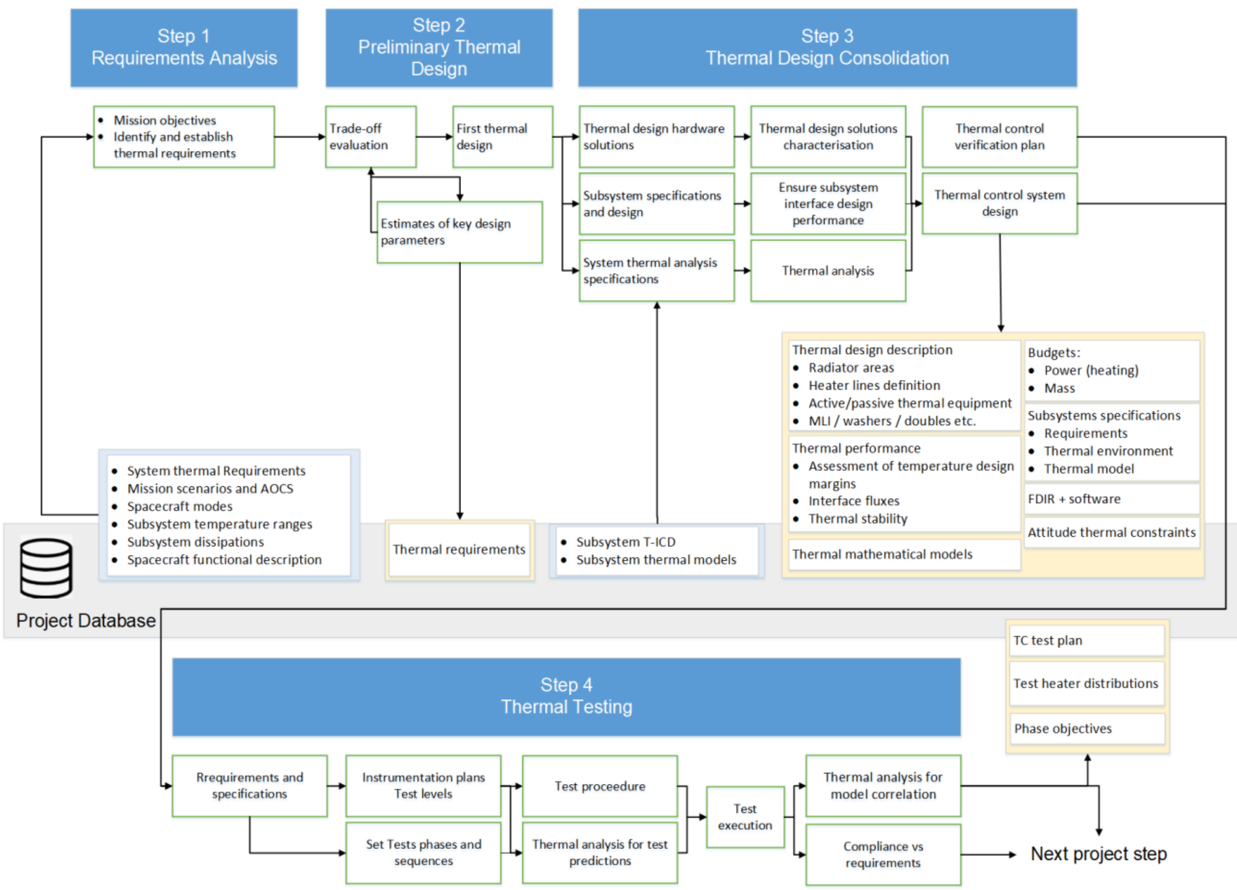

Figure 3. Abbreviated typical thermal engineering tasks. *One of the first steps in digitalization is to determine how processes can be described, categorized and associated with input and output data.*

Each task in Figure 3 can be expanded with a detailed description including lists of all inputs and outputs needed to perform to work. Table 2 outlines a process to produce an initial estimation of a thermal design, typically performed during phase-A studies. Table 1 presents two examples of tasks for the definition of heating lines and budgets for the thermal control system.

Task name	**Description**	**Inputs**	**Outputs**
Initial estimation of key parameters	To compute initial estimates of radiators areas and heater power There are several options, at the choice of the engineer: • Hand calculations / Excel spreadsheets • Simplified thermal model simulated with a thermal analysis tool • Usage of internal tools and calculators	Thermal pointing profile Thermal dissipation profile Sink temperatures + rejection capacitances = f(scenario) Thermal specifications	Radiators areas Heating budget need (powers, heaters, thermistors)

Table 2. Example of initial thermal sizing task description

Task name	**Description**	**Inputs**	**Outputs**
Create heater power budget	Deliver the total heating budget per sizing case	Active thermal control needs	Heater power budget
Establish heating line requirements	Heaters Definition • Power density, dimensions, resistance • Type Thermistors Definition • Temperatures ranges, uncertainties • Type, numbers • On-board allocation with electrical engineer Control Laws • Thresholds per spacecraft modes • Power allocation with power engineer	Subsystem thermal performance Design assessment Passive thermal control needs Active thermal control needs	Heater line requirements

Table 3. Examples of heater sizing and budget task descriptions

In the above examples, the requested data to perform the task is identified together with the associated stakeholders. From the task to *establish heating line requirements*, it is evident that interfaces with the electrical sub-system are important. The electrical engineer is expected to provide dissipations of each subsystem as a function of the spacecraft mode. At the end of the task, the data authored by the thermal engineer is provided for further processing by other stakeholders. For example, radiator areas will be used by the configuration engineer and heating budgets by the system/electrical engineer to establish system power budgets.

Repeating this operation for all tasks produces a list of the data to be used or authored in space thermal engineering and improves the overall understanding of workflows in a project. Moreover, it highlights areas where data consistency is important and where errors might lead to multiplied inaccuracies in downstream tasks. In the above example, the equipment dissipation data consistency is key to ensure the robustness and feasibility of the thermal control system design.

Typically, design data is often stored in documents, making it more difficult to ensure robustness of the data. Therefore, by providing a machine interpretable format of all engineering data coupled to computing infrastructures, digitalization can improve data access from each discipline while maintaining consistency.

One approach is to create a data structure for each *item* (i.e. equipment or element) used in the frame of a project, with any generated terminology harmonized in an ontology . In the frame of the OSMoSE project[3], one of the objectives is to deploy such a capability to help the implementation of digitalization across the space sector. Some preliminary work has been performed in the thermal domain at ESA to provide some data modelling to support the space system ontology development.

B. Data modelling of spacecraft items

Each *item* of a spacecraft from a thermal perspective can be decomposed into a number of categories (outlined in Figure 4):

- **Specifications**
  Each *item* must comply with thermal specifications such as temperatures levels, stability criteria, interface fluxes, heat transport capacity etc.
- **Role / Functional**
  Each spacecraft *item* has a dedicated role and function from a system point of view. This function might be described at discipline level to show the different usage and importance. For example, from an communications perspective, an RF transmitter has a primary function to fulfill the spacecraft communication requirements. In contrast, it does not typically have a useful function from a thermal perspective.
- **Analysis model**
  In order to transition from the design world to the simulation world, an analysis model to estimate the *item* performance might be required. This could include a dedicated data model or format to represent the *item*.
- **Thermal control**
  Each spacecraft sub-system may have a thermal control system based on passive means (coatings, materials, thermal fillers, and phase-change materials etc.) and/or active means (heating lines, coolers). Other relevant data might also be stored: thermal control type of an equipment, calibration function for thermistors, and temperature/resistance dependency for heaters.
- **Geometrical representation**
  From a thermal perspective, it is common practice to maintain a simplified geometry representing the *item* with the associated thermal control means applied to it. For example, an electronic unit is often represented as an aggregation of simple geometry (i.e. cube, quadrangles etc.) with references to dedicated coatings or mounting assumptions.

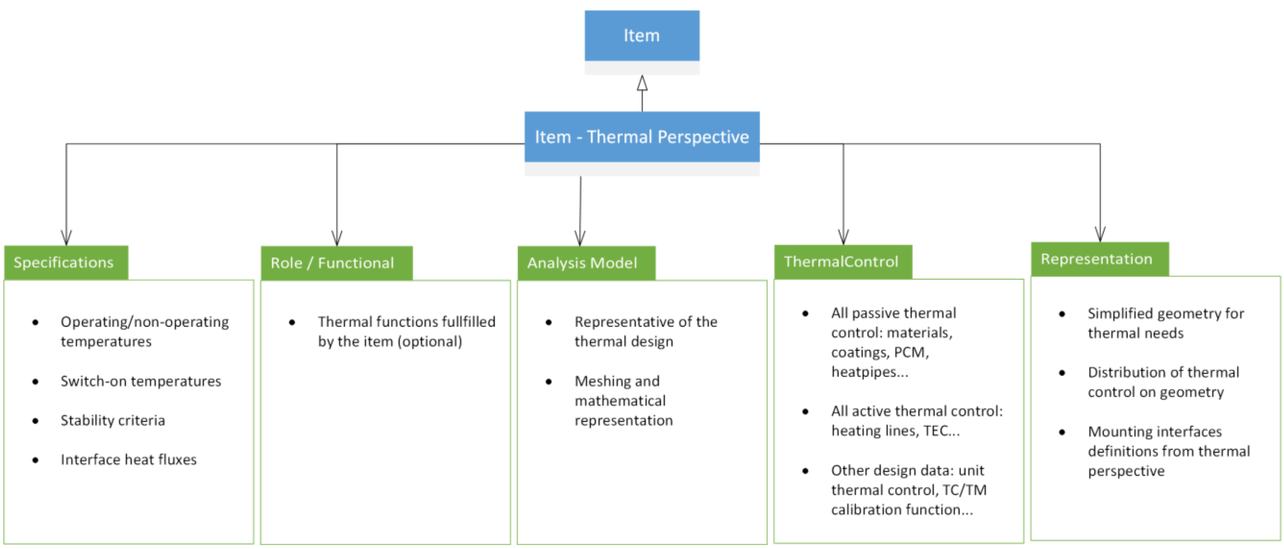

Figure 4. Example decomposition of a spacecraft item. *This example shows, from a thermal perspective, how a data model of the item might categorize and hold various types of data.*

Figure 5, applies the *item* data model to a typical spacecraft honeycomb panel. The structure will look different for each discipline. From a thermal perspective, a satellite honeycomb panel representation might be seen as a polygon with holes and dedicated subareas with associated coatings, materials, and thicknesses. On the other hand, from a structural engineering perspective, the panel may be viewed as a 3D structure where the locations of screw and insert patterns would be more relevant.

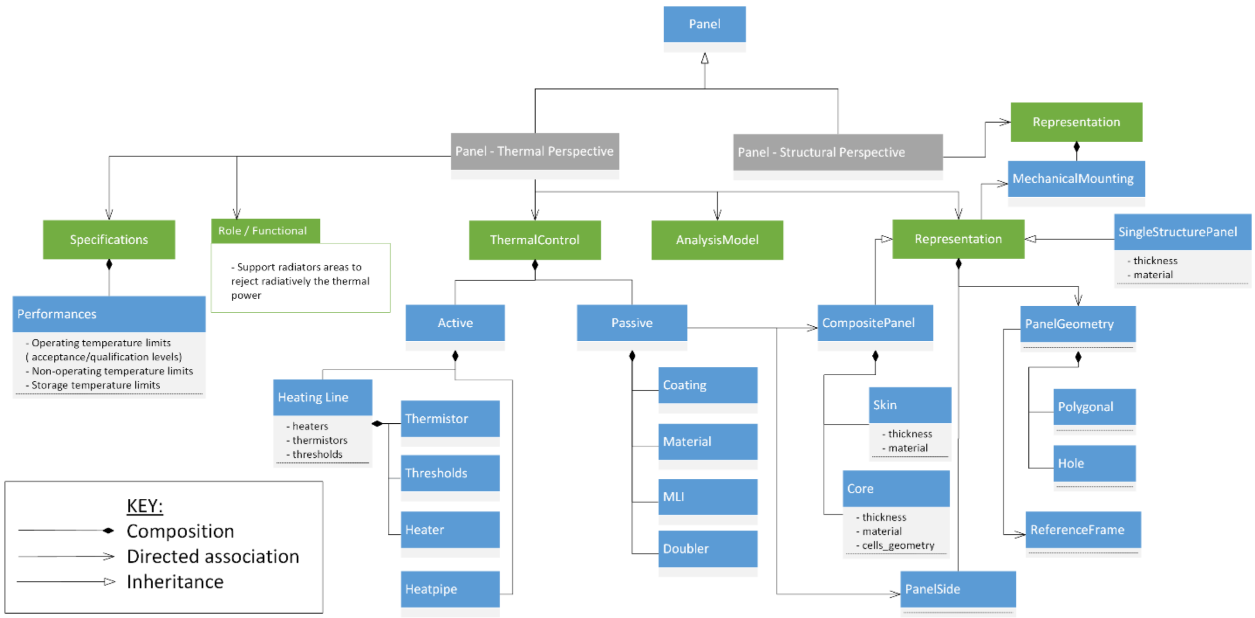

Figure 5. Informal decomposition of a spacecraft panel from a thermal perspective in UML. *The grey blocks represent different discipline perspectives, the green blocks represent categories and the blue blocks represent data classes with attributes*

Based on the above process identification, work has begun internally at ESA to contribute to an ontology of the thermal subsystem, using Object Role Modelling (ORM). ORM is an example of a semantic data modeling language used to describe facts and relationships between entities. One of the objectives was to embed the ontology in the overall Space System Ontology (OSMoSE), and to ensure traceability for each subsystem and consistency at their interfaces. The ontology will represent the data which has been authored and requested by each subsystem.

Figure 6, gives a high level view of data authoring from a thermal perspective using ORM. Facts are described and can be verbalized, i.e. "*The Thermal Control is managed by Active or Passive means*". ORM uses fact types and constraints to describe the model objects, for example with uniqueness, mandatory, or equality constraints. These are presented graphically as rectangular boxes which consist of constraint notation accompanied by a descriptive verb.

The previous example is extended to the modelling of a spacecraft panel using ORM in Figure 7. A distinction is made between the data a thermal engineer is requested to author versus data requested from other disciplines. For example, in order for the thermal engineer to define the conductance between spacecraft panels, the panel mounting assumptions must be known, i.e. cleats and insert design details. These assumptions originate from the structural perspective and may be exchanged with the thermal perspective via the data model. In the future, all authored and requested data in thermal engineering will be described through a similar ontology, for a future usage in the frame of MBSE and space system digitalization activities at ESA.

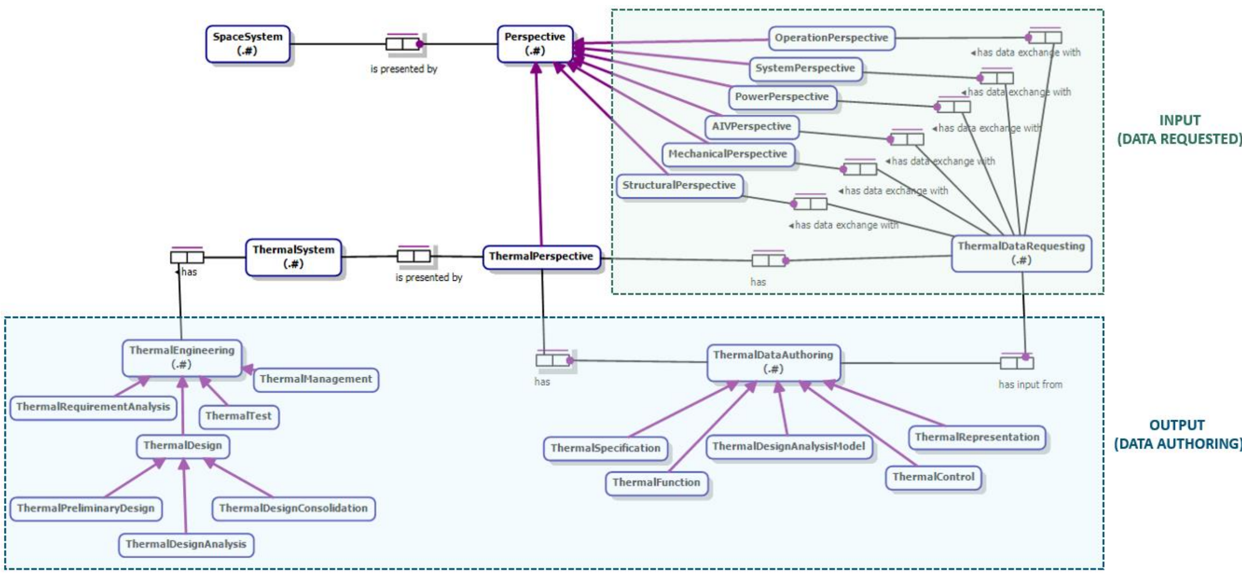

Figure 6. Object Role Modelling of thermal data authoring with links to other disciplines

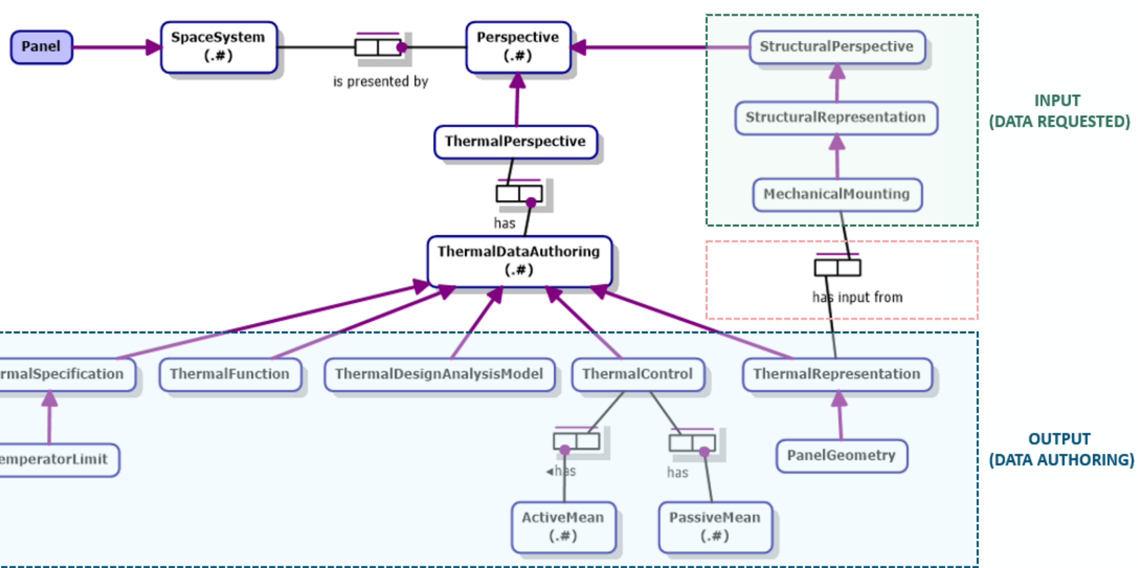

Figure 7. Object Role Modelling of a spacecraft panel

Application cases of data models are presented in the following section. It should be noted that the aforementioned data model was not available at the time of their development and therefore the examples highlight some of the challenges encountered due to its unavailability.

IV. Data model application cases

A. Thermo-elastic data pack delivery

The Resource Description Framework (RDF) is another example of a semantic modelling language, similar to ORM, with a number of applications on the web. The language permits relationships between entities to be expressed with facts. Figure 8 shows how RDF was used in a thermo-elastic test data pack delivery to describe relationships between data sources. The example covers a thermo-elastic demonstrator test[10] with the aim to produce a rich dataset to improve testing methods and to be made available for future studies. During the study, there was considerable overlap and data exchange between the mechanical and thermal disciplines. The challenge was that the data pack already existed and consisted of hundreds of documents in addition to raw and processed data in a variety of ad-hoc formats. This was considered as a barrier for newcomers working with the data due to the overwhelming amount of unstructured data to digest.

With the use of RDF, the thermo-elastic workflows were described with simple facts. Figure 8 can be used to describe that the *thermal model* has *thermal node sets* which maps to *finite element model element sets* via *mapping* with the predicate *maps to*. The results of a number of thermal analysis cases are related through the graph and describe the data sources used to perform the analysis. Moreover, each object in RDF can hold attribute data, for example the raw data, hyperlink to a document or format of a mapping given by *type*. Note that it is possible to express facts at a deeper level and describe how each individual thermocouple *maps to* a thermal model node. This highlights an example of a typical data modelling trade-off: to express data via layers of entities and relationships or to store the data directly as attributes. The facts represented in the graph describe the conceptual data model of the data pack and could be derived from an ontology. Furthermore, the data model can be transformed into a database structure or physical data model which may be queried to retrieve data.

This structure was also suitable for deployment on the web, where each subject was represented by an auto-generated webpage with hyperlinks to other linked objects. This improved the navigation of the data and made it easier to search. However, the data model was still constrained as most of the data had already been authored inside documents. A better approach would have been to store the data directly in accessible attributes of entities in a data model. This would have permitted easier scripting of the thermo-elastic workflows by reducing the number of ad-hoc scripts, manual data entry, and data format conversions. The graph presents a snapshot of a part of the data pack, but does not consider configuration control. One example would be to track improvements made to iterations of the thermal model during the correlation activity. Configuration control could be implemented by a history object, which could maintain a list of add, delete and update operations on the graph or build upon an established version control technology such as Git[11].

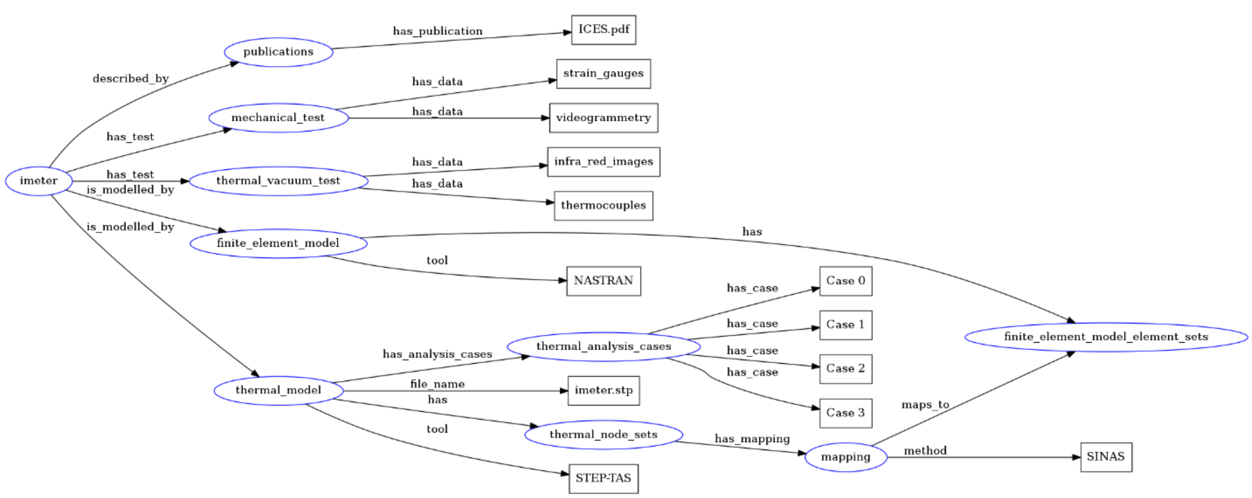

Figure 8. A conceptual data model of a thermo-elastic workflow using RDF

B. Links to spacecraft thermal testing and operations

The advantage of a digitalized thermal system is the potential for software tools to interact with the data model due to standardized data formats. Figure 9 shows an example of a thermal data exploitation tool developed in-house at ESTEC to visualize spacecraft telemetry and acquisitions in 3D (VISTA3D). The tool makes use of the existing thermal model and telemetry to present a live 3D interactive view of the hardware using a web browser. The tool can be used to explore temperature gradients and locate thermal sensors on the spacecraft. One key feature of the tool is the possibility to share a single view with just a hyperlink. The tool has been used in a number of application cases, for example for the Sentinel 2 mission to aid the training of spacecraft operators and to provide a live thermal status of the spacecraft. Moreover, the tool was recently used to support spacecraft thermal vacuum testing on two large ESA missions (JUICE and Metop-SG). For each of these complex spacecraft, a large amount of data was produced, in particular from the numerous installed thermocouples with locations that were often difficult to interpret from instrumentation plans alone.

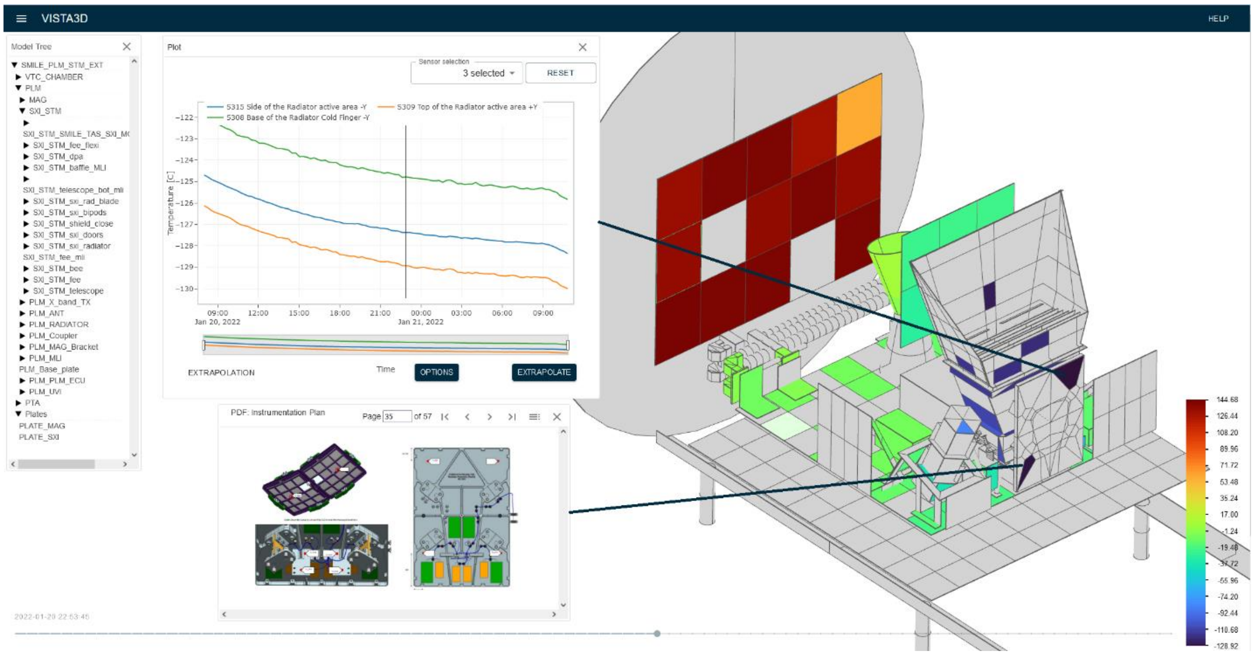

Figure 9: VISTA3D: Thermal test example showing color map, plotting and link to instrumentation plan

Nevertheless, the set-up of the tool for each project still requires significant manual work. This is often seen as a blocking point for industrial adoption due to the additional work load during busy phases of a project. The manual work includes preparation of the process inputs which must be transformed, often from PDFs and Excel documents, to JSON data structures for consumption by web technologies. In particular, the following inputs of the tool are authored by industry in wide range of formats:

- Geometric Mathematical Model (GMM)
- Mapping of thermal sensors, heater lines and dissipation to thermal model nodes
- Instrumentation plans and hardware photos

To address the first point, the tool reads the GMM in a STEP-TAS format, which permits reuse of existing adaptors that are already in place to most space thermal analysis tools. However, mapping and naming conventions pose a challenge. A single thermocouple may be referred to by a variety of names and numbers but also by previous naming conventions as defined during sub-system level tests. To overcome this problem a large mapping Excel spreadsheet is often maintained which is prone to human error. Similarly, instrumentation plans of thermal sensors and heater lines are often tables or images embedded in PDF documents. VISTA3D attempts to improve this problem by allowing the user to click on a sensor in the model and the corresponding page of the instrumentation plan is displayed as a pop-up. However in the future, this intermediate authoring step could be eliminated by direct reference to a 3D location in a CAD model.

An adaptor was developed to interface the tool with a number of test and flight data sources. This involved the conversion of the test data source from the original database to a local database where the data could be processed more quickly and easily. The intermediate storage format used was a simple HDF5 format holding timestamps and sensor values which permitted efficient slicing of the data. This additional work is expected to decrease in the future if the test and flight data can be made accessible in standardized formats.

One key area to work on is the mapping of data sources to models. The mapping shall allow a many-to-many representation of thermal hardware to model nodes, but shall also have the possibility to represent metadata about each sensor, for example 3D co-ordinates, physical units or links to non-digitalized documentation. This has already been addressed to a limited extent in the STEP-TAS standard, although at the time of writing this paper, has not yet been exploited. This is achieved by use of an *nrf_observable item* which maintains lists of references to relationships to other items (e.g. sensors, thermal nodes, conductors, and materials).

Digitalization can open the door for novel tools for thermal testing, such as temporal and spatial temperature extrapolation or on-the-fly model correlation. For example, a previously developed curve plotting and extrapolation tool was integrated in VISTA3D to predict the duration to the end of a balance test phase. As more of the inputs become available in digitalized and standardized formats, similar tools may simply work out of the box and therefore can potentially become more attractive for adoption in industry. The aim is to make the move to fully digital authoring systems and to minimize any additional work from the preparation of the required inputs.

V. Conclusions

This paper highlights some of the steps and considerations for digitalization of the space thermal engineering processes. A systematic approach to digitization of space thermal engineering processes is outlined, starting with process identification followed by conceptual data modelling. The authors are not proposing a specific technology or approach, however instead some ideas are discussed from a thermal perspective. The approach is not considered new for this application and has previously been successful at ESA in the sharing of design data for MBSE applications (in particular in the Concurrent Design Facility at ESTEC). One of the major challenges is the agreement of the terminology and ontologies to conceptualize the data. To address this, it is preferable to build upon existing open standards, but this requires consensus between ESA, industry, and other stakeholders. Other expected challenges include the ease of use of a data model for engineers and in particular how to populate it with data efficiently and systematically.

Some novel data model application cases are presented and act as a showcase to highlight the benefits of digitalization. When data is accessible in a more standardized way, this is expected to open the door for tool developers. It will also permit tools to be more easily adapted to other projects as the data format will be already enforced at the point when the data is authored. Therefore, the digitalization of thermal engineering processes is seen as an enabling building block upon which other technologies can eventually profit.

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