Using A Model-Based Systems Engineering Approach For Exploration Medical System Development

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Abstract

NASA's Human Research Program's Exploration Medical Capabilities (ExMC) element is defining the medical system needs for exploration class missions. ExMC's Systems Engineering (SE) team will play a critical role in successful design and implementation of the medical system into exploration vehicles. The team's mission is to "Define, develop, validate, and manage the technical system design needed to implement exploration medical capabilities for Mars and test the design in a progression of proving grounds." Development of the medical system is being conducted in parallel with exploration mission architecture and vehicle design development. Successful implementation of the medical system in this environment will require a robust systems engineering approach to enable technical communication across communities to create a common mental model of the emergent engineering and medical systems. Model-Based Systems Engineering (MBSE) improves shared understanding of system needs and constraints between stakeholders and offers a common language for analysis. The ExMC SE team is using MBSE techniques to define operational needs, decompose requirements and architecture, and identify medical capabilities needed to support human exploration. Systems Modeling Language (SysML) is the specific language the SE team is utilizing, within an MBSE approach, to model the medical system functional needs, requirements, and architecture. Modeling methods are being developed through the practice of MBSE within the team, and tools are being selected to support meta-data exchange as integration points to other system models are identified. Use of MBSE is supporting the development of relationships across disciplines and NASA Centers to build trust and enable teamwork, enhance visibility of team goals, foster a culture of unbiased learning and serving, and be responsive to customer needs. The MBSE approach to medical system design offers a paradigm shift toward greater integration between vehicle and the medical system and directly supports the transition of Earth-reliant ISS operations to the Earth-independent operations envisioned for Mars. Here, we describe the methods and approach to building this integrated model.

Keywords: Model Based Systems Engineering, medical system, Mars transit, exploration, human spaceflight

Acronyms/Abbreviations

Crew Health and Performance System (CHPS)
Deep Space Gateway (DSG)
Deep Space Transit (DST)
Exploration Medical Capabilities (ExMC)
International Space Station (ISS)
Model Based Systems Engineering (MBSE)
National Aeronautics and Space Administration (NASA)
System Architecture Model (SAM)
Systems Engineering (SE)

1. Introduction

NASA's Human Research Program's Exploration Medical Capabilities (ExMC) element is defining the medical system needs for exploration class missions. Development of the medical system is being conducted in parallel with exploration mission architecture and vehicle design development. Successful implementation of the medical system in this environment will require a robust systems engineering approach to enable technical communication across communities and creation of a common approach to the design of the emergent engineering and medical systems. A series of stepping-stone testbeds on Earth and in space will be utilized for maturation of medical system products based on the development work currently underway. Here we describe the establishment of collaborative tools to support the model infrastructure, the capture of stakeholder needs, design of the model architecture and emerging technical content, interaction with owners of related models to coordinate model expansion, and early work in coordination with integrating templates, conventions, libraries and practices common to all interacting system and subsystem modeling teams.

2. Model-Based Systems Engineering (MBSE) Infrastructure

Model infrastructure is an important foundational element because it forms the underlying framework to implement MBSE. Infrastructure design will have long-term consequences and impact the effectiveness of the overall modelling effort. The major components of model infrastructure include the tools, processes, and project team (Fig. 1).

Fig. 1. Model infrastructure includes the project team, process and tools.

Given previous institutional experience, The ExMC Systems Engineering (SE) team selected the Systems Modeling Language (SysML) as the modeling language to support this work. The medical system model will have an early integration point with a broader exploration habitat model, and SysML serves as a common tool between these two working groups. The habitat team had basic infrastructure established such as selection of MagicDraw as the modeling software, and had set up shared licenses. The two working groups synchronized use of software versions to allow for streamlined sharing and integration of products. The ExMC SE and habitat teams decided to use a NASA-wide teamwork server, which allows the geographically diverse and cross-agency group to readily access the working model. Use of the teamwork server also enables more efficient model integration and sharing of information as everyone is using the same server to store their models. Utilizing these shared resources resulted in significant time and cost savings for the setup and management of the software licenses and teamwork server.

ExMC worked with teams at JSC and across the agency to understand the processes required to update modeling tools and servers, and tailor some of them to fit the ExMC SE needs. One of the most important set of processes from a model infrastructure perspective is managing the system model on the teamwork server. To avoid overwriting someone's work and maintain model integrity, a process for check-in of the system model, locking model elements and reverting to previous versions was established for the ExMC team. NASA uses a standard process for managing access to information systems and this system is used to manage access to the teamwork server. A user's guide was developed to familiarize and train system modelers in proper implementation of the process work flow.

The ExMC team that initiated the medical system model participated in a SysML training course at the onset of model development, which created a core MBSE modeling skillset within the team. Team members also strengthened their understanding of systems engineering principles and practices prior to implementing MBSE. Roles and responsibilities of model team members were established, although they evolved as the modeling tasks and team members' availability ebbed and flowed over various months. Building relationships within the broader organization's modeling community is another important aspect to establishing model infrastructure, and allows each project to leverage previous work for more effective integration and optimal medical system design. ExMC SE team members participated in MBSE activities with other groups whenever possible to establish community relationships. As the medical system is part of the overall vehicle system, speaking a common technical language with engineering partners is essential to successful integration of the medical system.

3. MBSE Context and Approach

Before technical work was initiated, the team spent time focused on organizational awareness, identification of customers and stakeholders, and identifying where this work would add value across the agency. Understanding customer needs and expectations across levels of management are key philosophical elements to success of any project, particularly within a large multi-tiered organization. Once the technical and modeling work began, it was key to establish a general process of model development. The medical system and habitat modeling teams participated in a joint training course on MBSE methodology, which further strengthened the common mental model and modeling practices used between the working groups. Following the methodology training, a phased modeling design was formulated to best meet the needs of the working groups. The team also established a modeling process to ensure the model was inclusive of the components to move from identification of the problem space, to establishment of requirements, and eventually verification and validation of the resultant solutions. A style guide is in development to further define a common set of modeling practices and implementation procedures, as related to the use of SysML, MagicDraw, and implementation in these NASA specific models.

A recurring question the teams face is 'how do you know when you are done modeling?'. There is no obvious answer to this question, and limitations will exist in development and application of the final product. As much as possible, these limitations exist due to conscious design choices and are documented for future discussion and review. Here, the thought process in defining a methodology that best suites the needs of these NASA teams is described.

3.1 Organizational Value & Key Philosophy

During formulation of the ExMC SE team, a mission statement was drafted along with identification of the needs, approach, benefits, and evaluation of organizational culture. This was important to establish best practices, offer value proposition, and help to keep the modeling work focused on the needs of the medical system design.

<u>*Mission Statement*</u>

Define, develop, validate, and manage the technical system design needed to implement exploration medical capabilities for Mars and test the design in a progression of proving grounds.

With the above Mission Statement in place to keep the team focused, the model itself was initiated with early stakeholder buy-in and advocacy from many tiers of management. The central mission is important to ensure that the task at hand, to design the Mars transit Medical System, does not get overburdened or unduly influenced by competing priorities of other subsystems, but rather streamlines future integration with the most robust design achievable to meet crew health needs.

3.2 Phased Model Development

When applying the modeling process, developers can easily lose sight of the value and purpose that the model can serve for systems engineers. The problem is especially true when the team is learning the methods and tools for the first time. The issue is further complicated when attempting to organize and integrate across disparate system domains, where vocabulary and even modeling standards can be different.

One approach to mitigate this concern is to provide clear guidance early in the process in an attempt to focus model development. The teams developed guidance (Fig. 2) to shape the modeling work. The guidance was organized into 4 generic life cycle development phases, and describes the model context, content, and outcomes. Specifically, the teams are:

1) Defining the *Context* and activities in each phase of the project lifecycle, to clarify the level of detail expected in the model,
2) Identifying the *Model Content*, to define what elements of the modeling process should be applied at that phase, and
3) Listing the *Model Outcomes*, to develop a form that can be interpreted by stakeholders to demonstrate value (and which may have to be transformed from the model to ease communication).

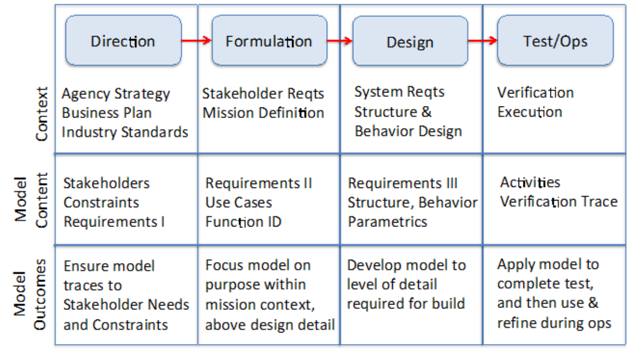

Fig. 2. Defining model context, content and outcomes by phase focuses model development.

During the Direction phase, the model should capture the guidance from the highest levels of the organization. Whether at an agency level of government, or the level of business strategy in the commercial world, identifying this direction ensures the model is aligned with top level strategy. This direction can be provided in the form of agency strategy documents, business plans, or even marketing products. Also, the particular activity may have to comply with a number of industry standards and safety contstraints. These products are often independent of a particular project. This important direction can be captured early in the modeling process, then reused and leveraged by other projects.

During Forumulation, the Project Manager and Systems Engineer must develop the detail required to ensure the project products meet stakeholder needs. It is at this phase, that a high level Design Reference Mission and Concept of Operations can be developed to help guide early design trades. It is tempting to use the modeling process to jump to design detail, especially if the model is developed by subsystem domain experts. If done correctly, this phase avoids early specification of design detail in order to leave as many options available as possible.

Once stakeholder needs have been clearly identified in the Direction phase, and then linked to the Project Formulation products, then the work of detailed Design can begin. System requirements are generated, system functional decomposition can be matured, and system activities and behaviors can be specified.

Finally, the model can be applied to the Test phase of the project lifecycle. The as-built system can be traced back to design specification as well as system and stakeholder requirements. Importantly, the model of the *test archiecture itself* can be very valuable during this phase. Not only does the model support specification of activities of the system during operation, but it can also describe the test activities themselves. Important products such as the interfaces between the unit under test and the test archiecture can be clearly identified and traced back to the requirements.

This approach to identifying the different project lifecycle phases, and the purpose and focus of each phase, can help the development team properly apply the modeling process in a methodical way. This process can be iterative, so that analyses performed can provide feedback within the phases as needed. This can be done to correct errors of reqiurements specification, or to redirect design when issue of development are encountered.

3.3 Medical System Model Domain

A key early activity in MBSE is to define the domain for the system of interest. As shown in Fig. 3, the Medical System is represented by the central yellow boxes and resides within a broader Crew Health and Performance System (CHPS). The CHPS in turn, is represented within the larger Flight System (or habitat, as in the context of the deep space exploraiton missions). Descriptions of the blocks and parts shown in Fig. 3 are described in greater detail by Mindock et al. [1].

An important aspect of this domain figure is the inclusion of the crewmembers within the Flight System. In a first iteration of the model, the team represented the crewmembers *outside* of the Flight System and Ground System blocks, showing interactions with both. That initial view supported focus on the technical systems that are to be designed and built. However, as the team worked through subsequent model content, they recognized an increased need to promote awareness and understanding of the impacts the integrated human and technical portions of the system have on each other. At that time, the decision was made to represent the crewmembers, with the relevant mission medical roles, within the Flight System. Moving forward, the team advocates for models of the Ground System to adopt a similar approach.

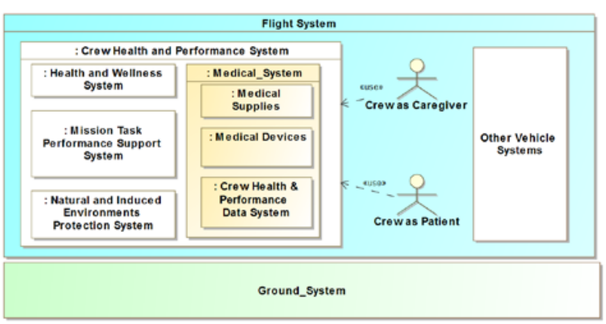

Fig 3.This diagram shows representation of the Medical System as an internal component of the CHPS, and communicates that the crewmembers are important components within the Flight System.

4. Medical System Model Design

A work flow and modeling process has been established within the ExMC medical modeling team, and has been coordinated with the habitat modeling team, to share and borrow best practices between the two teams in an effort to create products that can easily be shared and integrated between the working groups. Here, we describe how the process starts with development and utilization of a ConOps document and clearly defined use case scenarios, the organizational structure of model packages, and initial modeling process. The technical content developed to date allowed for generation of a medical system functional decomposition and initial system architecture.

4.1 Concept of Operations

The development of an effective medical system model must include the identification and documentation of the problems to be solved (stakeholder concerns), the expected abilities of the system (needs), and the specific ideologies by which the system will be designed (goals). This content was initially developed in a Concept of Operations (ConOps) document [2], which uses a set of diverse medical scenarios to explore the various types of care that may be required to prevent, diagnose, treat, and provide long-term management of medical conditions during a Mars exploration mission.

By adjusting mission and system parameters, such as communication availability, biomonitoring capabilities, and the urgency of care, each scenario provides a unique use case that outlines areas of stakeholder concerns and highlights potential needs the system must fulfill. Each scenario consists of narrative text and a flow chart of expected activities. Collectively, these ConOps scenarios represent a wide range of possible medical capabilities and provide a high-level operational description of the system.

As the ConOps was a mature product at the start of the medical system model development, a decision was made to treat the ConOps as a source document for aiding in requirements development and to reference it from within the model, instead of incorporating all content directly into the model. The SysML model developed by the ExMC SE team to capture ConOps content is refered to as the Deep Space Transit (DST) model in this paper.

4.2 Model Organization

A common template for model organization ensures consistency in development of model products and when adopted across teams, makes navigation through shared models easier. In the MagicDraw tool, the model is organized into files, or ‘packages’, within a containment tree. Within our team, the containment tree for the DST model has been organized to include the following packages:

01_Model Intro
02_Stakeholders
03_Stakeholder Concerns

04_CHP Behavioral Model
05_CHP Structural Model
06_CHP Requirements
07_CHP Traceability
08_V&V Planning
09_Action Items
10_Questions
11_Value types

Each of these packages hold content unique to these topic areas, but are used consistently between models. For example, Package 04 contains the following internal structure of packages:

01_Medical System Activity Library
02_Crew Health Perf Scenario Trees
03_Medical System Scenario Act Diags
04_Medical System Activity Decomp
05_CHP Interactions Seq Diags
06_Medical Subsystem Scenario Act Diags
07_CHP Functions

It is worth noting that the highest-level packages are at the level of the CHP System, with Medical System content typically housed inside. The Medical System content is the current focus of the ExMC SE team, but it is anticipated other CHPS areas will be populated in the future by working with other CHPS disciplines. The DST model represents the most detailed and comprehensive Crew Health and Performance model this team is developing. Models are also in development for shorter duration exploration missions, such as the Deep Space Gateway (DSG) design reference mission, which is intended for a vehicle resident in cis-lunar space. The medical system will not be as robust in the DSG, and the model will likely only require a subset of the content being development within the DST model. However, following the same modeling practices and procedures will ensure the content that is included, is consistent and mirrors that in the higher fidelity models.

4.3 Defining the Modeling Process

The process shown in Fig. 4 describes the workflow used to develop model products captured inside the packages described in Section 4.2. The use case scenarios from the ConOps were used as the starting point to develop behavioral diagrams such as activity and sequence diagrams, and the follow-on functional decomposition, all of which help to define the problem space within the model. Next, system and subsystem requirements will be generated and captured. The modeling process shows this as a looped and iterative process, which allows for model updates as needs are negotiated and trades are made throughout the project lifecycle. A detailed description of content included in this workflow is described in Mindock et al. [1].

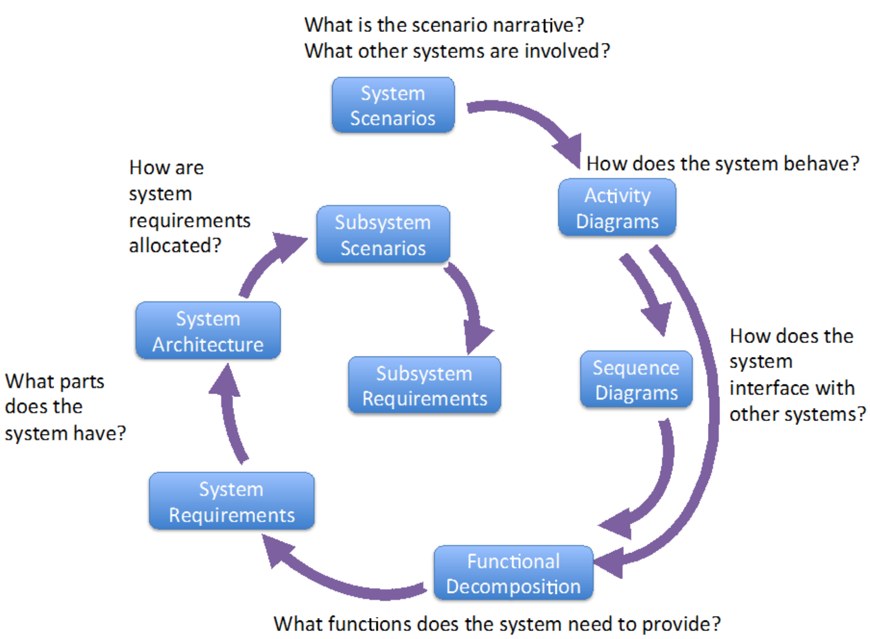

Fig 4. The initial modeling process highlights the steps of developing behavioral diagrams, conducting a functional decomposition, and deriving system architecture and requirements.

4.4 *Functional Decomposition*

While the development of the SysML activity and sequence diagrams based on ConOps content was relatively straightforward, development of a medical system functional decomposition required additional analysis described here. A function describes what the system does. Thematic analysis was used to identify what the functions were for the medical system. The six-phase approach outlined in Braun and Clarke [3] was used for the analysis. Below are the six phases with insight on performing each phase.

Phase 1 - Familiarization with the data: During this phase the ConOps and activity diagrams produced from the ConOps were reviewed several times in search of patterns (i.e., groupings of activities with a common function). While reading, text was tagged with notes on potential functions.

Phase 2 – Generating initial codes: Inductive coding, codes derived from the data itself [4], was used to create the initial set of codes.

Phase 3 – Searching for themes: In this phase initial codes were written down on pieces of paper and moved around into groups to form overarching functions. During this phase relationships between codes and other functions were assessed.

Phase 4 – Reviewing themes: Candidate functions generated in phase 3 were refined. Refining involved merging or separating functions to ensure that each function was clearly distinguishable from another function (i.e., no overlapping in meaning).

Phase 5 – Defining and naming themes: A couple sentence description of each function was created and a brief name that covered the essence of the function was provided.

Phase 6 – Producing the report: Instead of producing a report, functions were entered into the SysML model as block definition diagrams, such as in Fig. 5. Supporting diagrams showing the mapping of the functions to the activities (based on ConOps content and modeled in activity diagrams) that made up these functions. This allows traceability from the ConOps to the high level system functions.

Throughout this entire process a constant comparison was conducted [5, 6]. This method helps identify commonalities amongst the activities within each function and between functions. Activities that fit better in a different function were moved and functions that were too broad were separated into more specific functions or too similar were merged. Memos on possible changes to the coding and functions were documented through all phases. As functions were created they were discussed with the modeling team. Notes taken during these meetings were used to update the functions. Identified functions from this decomposition will assist in the development of the medical system architecture and functional requirements.

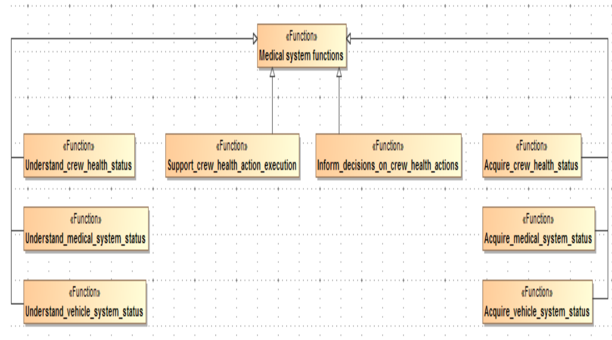

Fig 5. High-level functional decomposition content informs medical system requirements.

4.5 Architecture

Although medical system requirements are not yet in place, work on the architecture was initiated to help the ExMC team converge on the same mental model and terminology, and to allow communication with the wide range of stakeholders. In SysML, the terminology of "structure", or a structural diagram, is utilized to represent the hierarchically arranged items of interest in a system of interest. Each item in the structure has two primary characteristics, 1) contained data, and 2) implemented operations that affect that data. These items, when organizationally presented, become the system architecture blocks. While the data and operations are not yet comprehensively defined for the medical system, naming, organizing and describing the system blocks are useful first steps in architecture development.

Currently ExMC has approached definitions of model structure from both bottoms-up and top-down viewpoints. Fig. 5 arrives at a structure, from a decomposition of required activities into an organization and assignment of those activities to responsible blocks. The blocks must then contain data items that are responsible for or required to use in the implementation of the block operations. From a top-down approach the medical system architecture can also be arranged with considerations being focused on broader programmatic categorizations of items with associated data and operations. Fig. 6 shows the medical system architecture considering overarching issues such as interactions with programmatic elements outside of ExMC, and ownership of activities. Items within the scope of ExMC work are shown as the same yellow boxes as in Fig. 3 in Section 3.3, with red boxes representing work within the scope of ExMC at a lower level of detail. The red boxes fall into two organizing blocks, The Medical System block and the Mission Task Performance Support System block, where the former block will be influenced by ExMC medical system iterations. ExMC activities will influence the latter, but other systems throughout the Flight System will, as well, so the Mission Task Performance Support System is not shaded yellow. These two blocks are shown as parts of the larger Crew Health and Performance System, consistent with the higher level Fig. 3 in Section 3.3

Use of system parts by relevant persons or other resources, such as the MCC "Mission Control Center" personnel, are represented, also. From the SysML project management goal of having a "one source of truth" model for all interested parties to draw upon, the architecture of Fig. 6 is intended to be the entrance point for all medical system participants. This singular data integration point becomes the System Architecture Model (SAM) for ExMC.

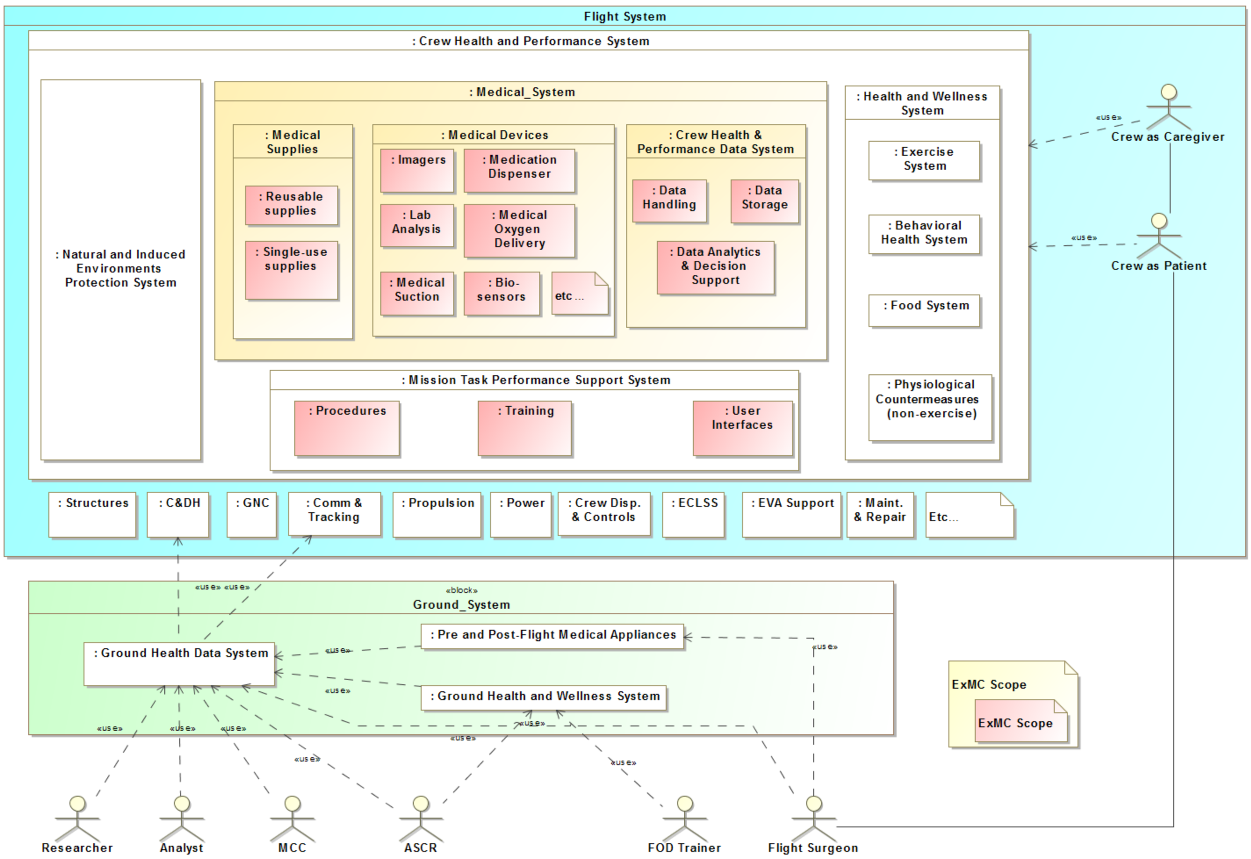

Fig. 6. This high-level medical system architecture and context provides a common model for many stakeholders.

5. Next Steps in Medical System Model Development

The medical system is one system within the larger Flight System. Data generated within the medical system will be inputs to other systems and vice versa. Interfaces between the different systems that make up the larger system need to be defined and modeled to understand how all these systems work together and support one another.

5.1 Interface Definitions and Model Expansion

Based on discussions with stakeholders, relevant existing documents reviewed, and the ConOps, example interfaces from the medical system with other systems have been identified. For instance, medical grade oxygen will be needed by the medical system to treat patients. The Environmental Control and Life Support System (ECLSS) will likely provide this oxygen. Meetings are being held with different system groups to understand their needs, goals, objectives, and requirements, and to negotiate how the systems should be integrated. Through these meetings model content will be created, iterated, and trades amongst these systems will be performed.

5.2 Customized Tools

Customized tools are being developed to add consistency, exportable documentation, and traceability throughout the model. Tools emerging for use between the medical system and habitat modeling teams include common model libraries, profiles, stereotypes, and style guidelines. Small example projects relevant to the work at hand are often used to test the value and utility of these tools before full implementation.

5.2.1 Model Libraries, Profiles, and Stereotypes

From the very beginning of the model development process, teams should be aware of models and products that can be captured and reused. Products like unit specification can be applied by a number of projects. Common system components such as power or data can also be captured, at various levels of detail. Libraries included in the DST model include the NASA Model Library, developed by the habitat team. Libraries specific to the medical system include a medical system activity library, and a medical system signal library capturing interactions between the medical system, crewmembers, and other flight and ground systems. The DST model also uses a profile, containing applicable SysML stereotypes, created by the habitat group. This is another way to increase effectiveness in integration.

5.2.2 Model Style Guidelines

As the team becomes more familiar with the modeling process, success and failures in development can lead to the creation of Style Guidelines. Successful approaches to look-and-feel of diagrams, common techniques of model breakdown, and specification of common vocabulary can be captured in a set of guidelines for the next project development cycle. A Style Guide in development will include methods, workflow, and guidance on use of notation and color codes for various model components. It will also provide guidance on common use of data flow direction. For example, all model inputs should be visualized coming into a frame or port from the top or left of a diagram frame, and output should flow out through the right or bottom of a port or frame.

6. Future Applications

Taking a model-centric approach in developing the medical system's influence on crewed space exploration missions and vehicle design is expected to provide several useful features enabling a dynamic exploration of architectures to evolve and mature as the exploration program itself matures.

From a document-centric viewpoint of assuring all NASA System Engineering requirements are met, those program documents that still may be required are planned to be auto-generated from the SAM. Requirements tracking and V&V activities will also be accessed and tracked in the SysML environment. Criteria to meet NASA mission phase design reviews will be allocated in the model and ideally access to associated review data will be accessible from the SAM.

An important model use in Phase A/B studies particularly is to perform system level trades. Different design features will impact Figure of Merit ratings that, thru decision analysis assessment, provide system architects a measure of how mission parameters and vehicle design details impact system performance. This early stage trade study / decision analysis process is desired to be greatly automated by incorporating SysML executable model features. Executable models perform system simulations and output measures of effectiveness and performance that can roll up in a decision tree process to understand the highest level Figure of Merit pro's and con's.

Such a broad reaching SAM as ExMC envisions, and with aspects which dig down deep enough to investigate quantified element and sub-element performance impacts on architecture performance can become a powerful tool for the acquisition process, as well. If the NASA model block definitions of data and operations are requested as features which suppliers can implement in their own SysML modeling, an interchange of model requirements – defined by NASA and component performance – returned by the supplier, could define a "plug and play" acquisition environment for ExMC projects.

Other tools to support the ExMC systems engineering processes are currently being developed, and one of the near-term efforts of the broader ExMC team will be to allow interplay among the tools. ExMC is creating an ecosystem of analysis tools to support medical system trade studies. Fig. 7 represents various tools that are a part of that ecosystem, shown in blue boxes and grouped broadly by categories. The first group on the left represents information describing how medicine will be practiced, such as what conditions will be planned for in-mission treatment (as in the Accepted Medical Condition List, or AMCL), planned medical activities (e.g., periodic physical exam), and needed medical capabilities (e.g., provide imaging). Next, information on implementation options is needed. For example, resources to provide capabilities are identified (e.g, an ultrasound to perform imaging, as captured in in a tool called MONSTR2). Implementation options must be characterized in terms important in space system development, such as mass, power and volume (in a tool called MEDMEL). Data estimates for medical activities must also be provided. ExMC is additionally developing a tool to estimate mission risk characteristics (MEDPRAT), and a capability to evaluate how well an exploration habitat accommodates medical workstation needs. Key outputs from these tools will be tied to parameters in the SysML model, allowing traceability to the system behavioral, structural, and requirements content. Information from various tools will need to be shared bi-directionally, and it is future work to determine the common repository, configuration, and data management implementation.

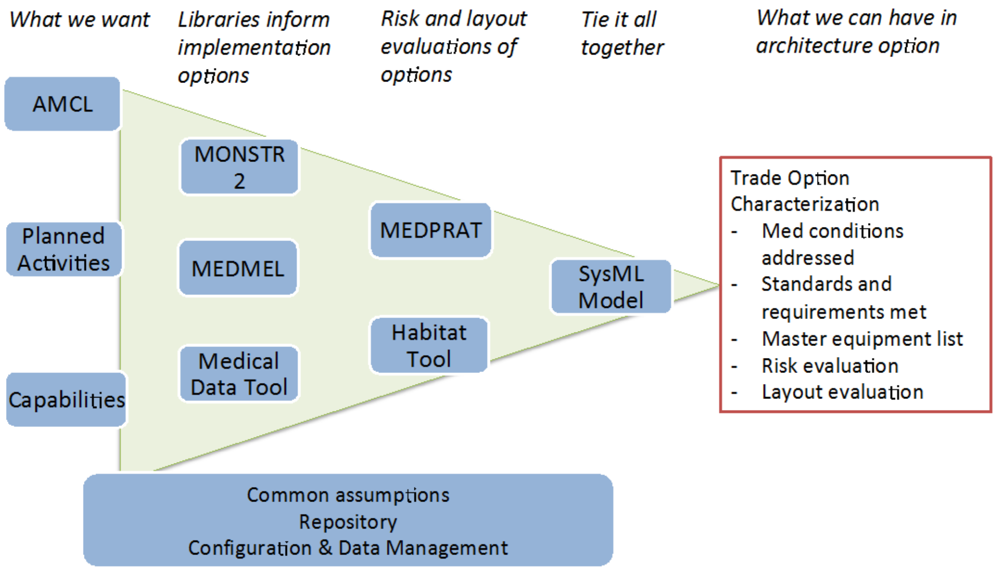

Fig. 7. ExMC systems engineering tools are in development to support system trades and analyses.

7. Conclusions

Successful implementation of any system or subsystem in a complex project, such as a Mars transit vehicle, requires thoughtful and structured design from project initiation through maturation and implementation. The MBSE approach is key to ensuring consistent workflow, practices, and streamlined integration with vehicle design. Here, we describe the methods, tools, and collaborative interactions that have helped to establish a working model, infrastructure, architecture, and early model of the medical system being designed for Mars transit. Throughout the life cycle of this exploration program requirements will ebb and flow, trades and resource negotiations will be made, and mission objectives will morph. The ExMC SE team is working in confidence that the design of a robust yet flexible SysML model of the medical system will stand the test of time, and ultimately define, develop, validate, and manage the technical system design needed to implement exploration medical capabilities for Mars transit missions.

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