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How Should Life Support Be Modeled and Simulated?

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Why do most space life support research groups build and investigate large models for systems simulation? The need for them seems accepted, but are we asking the right questions and solving the real problems? The modeling results leave many questions unanswered. How then should space life support be modeled and simulated? Life support system research and development uses modeling and simulation to study dynamic behavior as part of systems engineering and analysis. It is used to size material flows and buffers and plan contingent operations. A DoD sponsored study used the systems engineering approach to define a set of best practices for modeling and simulation. These best practices describe a systems engineering process of developing and validating requirements, defining and analyzing the model concept, and designing and testing the model. Other general principles for modeling and simulation are presented. Some specific additional advice includes performing a static analysis before developing a dynamic simulation, applying the mass and energy conservation laws, modeling on the appropriate system level, using simplified subsystem representations, designing the model to solve a specific problem, and testing the model on several different problems. Modeling and simulation is necessary in life support design but many problems are outside its scope.

Nomenclature

ALSS = Advanced Life Support System
ALSSAT = Advanced Life Support Sizing Analysis Tool
ARC = Ames Research Center
ARS = Air Revitalization System
ATCS = Active Thermal Control System
BLSS = Bioregenerative Life Support System
CELSS = Controlled Ecological Life Support System
DAWN = Design Assistant Workstation
DoD = Department of Defense
ECLSS = Environmental Control and Life Support System
ELISSA = Environment for Life Support System Simulation and Analysis
ESA = European Space Agency
ESM = Equivalent System Mass
EVA = ExtraVehicular Activity
IRLSS = Integrated Regenerative Life Support System
ISRU = In-Situ Resource Utilization
ISS = International Space Station
JSC = Johnson Space Center
KSC = Kennedy Space Center
LISSA = Life Support System Simulation and Analysis
M&S = Modeling and simulation
MELISSA = Micro-Ecological Life Support System Alternative
MSFC = Marshal Space Center
NSCORT = NASA Specialized Center of Research and Training
OCAM = Object-oriented CELSS Analysis and Modeling
SBES = Simulation-Based Engineering Science

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SCALISS = Scaling of Life Support Systems
SE = Systems Engineering
SIMOPT = SIMulation based OPTimization
V-HAB = Virtual Habitat

I. Introduction

THIS paper considers how to do modeling and simulation of space life support. Why have so many different life support systems modeling and simulation efforts been conducted over several decades by industry, government agencies, and universities? Why does everyone develop their own model rather than adopting someone else's model? If modeling and simulation is done to answer life support systems questions and define solutions, what are the design results? Why are there continued duplicative modeling efforts rather than a common approach and a shared body of knowledge?

If the purpose of developing a model and simulation is to design the next life support system, that purpose is not being served. The developers of models and simulations seem satisfied by the model development effort itself. There are few outside users of their products. The problem of sponsors funding developers to make a product that finds no users is common. It is better if the product is developed to satisfy a user requirement.

The sponsors and developers benefit significantly from the modeling effort, even if outside users do not. The developers gain creative professional skill and knowledge in developing the model and investigating its behavior. The process of developing a model provides more insight than simply using one. The model provides an organized view of life support. It allows defining and sharing modeling tasks and coordinating individual research projects. Using someone else's model to solve design problems would be much less effective.

The sponsors expect that the models will produce better understanding of life support. Models can help make decisions on engineering design, technology selection, and funding. The managers are intended beneficiaries, but not hands-on users of the models. If management is too concerned with maintaining existing organizations, technical programs, and staff, the modeling effort may not be asked to challenge assumptions or produce alternate concepts. The goal should be not simply to understand space life support, but to improve it to help provide safer and more cost-effective human exploration.

II. Modeling and simulation (M&S) background

Modeling and simulation (M&S) is an important computer methodology widely used in systems design to examine dynamic behavior. There have been significant results but much remains to be done. Expectations for M&S may have been too high but it seems more likely that M&S has not always been effectively used.

A. Why do modeling and simulation?

The essential purpose of M&S is to provide dynamic process experience and systems understanding that can help decision making. Using M&S to gain knowledge is generally much easier, cheaper, faster, and safer than building and testing actual hardware. It allows virtual testing and system optimization over a wider range of environmental parameters and internal states than could be tested in reality. (Wikipedia, Modeling and Simulation)

The need for M&S in system analysis seems too obvious to state, but there have been some strong specific justifications. "M&S is considered an integral part of systems engineering of military systems." (Wikipedia, Modeling and Simulation) "Simulation-Based Engineering Science (SBES, 2006) is a discipline indispensable to the nation's continued leadership in science and engineering." "Seldom have so many independent studies been in such agreement: simulation is a key element for achieving progress in engineering and science." "Computer simulation has become indispensable to the development of all other technologies." (SBES, 2006)

B. What can modeling and simulation accomplish?

M&S has created great expectations for decades. "We hope to solve the most stubborn problems of modeling, engineering design, manufacturing, and scientific inquiry." (SBES, 2006)

NASA life support systems research and development uses M&S as part of systems analysis. It is used to investigate the behavior of current and alternate systems architectures and to investigate operations and the effects of failures. The process of developing and running M&S provides a greater understanding of life support. Yet many design problems in space life support are not usually investigated using M&S, including integration and test, reliability and maintainability, and life cycle cost.

C. How should modeling and simulation be done?

The three fundamental initial tasks in modeling and simulation are:

1. Identify the right problem.
2. Apply the correct expertise.
3. Plan the effort correctly.

Considering the last task of planning, the systems engineering approach should be used to plan the M&S effort. A systems engineering based study of best practices that is reviewed below considers requirements, definition, design, development, and testing.

The study also emphasizes the need for subject matter expertise, such as in recycling space life support systems, over the knowledge of simulation techniques or software design. Many useful simulation software packages are available and some have been standard for decades. Probably the worst mistake in M&S is to redefine the actual engineering problem so that it fits within the selected M&S tool. M&S is not about techniques, or software tools, or even the model itself, but about helping to answer important system design questions.

There is no substitute for experience. People without experience make incorrect assumptions, ask the wrong questions, and solve the wrong problems. A general understanding of recycling space life support systems helps guide developing M&S. The model should be developed on the overall system level, using simplified black box representations of the subsystems. The model should show the mass flows and continually check conservation of mass of all the materials, water, oxygen, etc. A static analysis should check the steady state mass balance before dynamics were modeled and simulated. An expert knows which problems are currently solved or unsolved, which are important or unimportant, and which are suitable or unsuitable for M&S.

Identifying the right problem, having an important question that requires M&S, is the most fundamental consideration. A model should be designed to solve at least one specific problem, and if possible should handle a geenral class of problems. Sometimes a model intended to be general and all-inclusive requires extensive modification just to handle the first question that is asked of it. It would be unusual for an existing model to be able to solve a new problem without revision. A major problem with all-inclusive models is that they too broad, including many processes that do not affect the answer being sought. This produces opacity and confusion rather than clarity and understanding.

The overall space life support problem is developing a design that meets the requirements. Systems engineering requires many different analysis techniques. M&S is an important part, but only one part of systems engineering, shedding light on system performance, integration, dynamic operation, testing, operations, logistics, etc. All models are limited and based on assumptions. They can help make design choices but no one model can provide all the information needed for complex decisions involving many performance parameters.

III. Life support M&S general approach and specific problems

What would be in a general, all-inclusive model of space life support? What are some of the specific problems that should be addressed by a life support model and simulation?

A. A complete life support system model

A general, all-inclusive life support model should include the major subsystems of recycling life support: carbon dioxide removal, humidity removal, waste water collection and recycling, carbon dioxide reduction to water, and generation of oxygen from water by electrolysis.

The model should include the crew habitat's physical entities: the crew compartments, storage buffers, and material flow paths. It should simulate the required processes: recycling, resupply, and ExtraVehicular Activity (EVA). It should be able to model changes or failures: resupply delays, power failures, recycling system failures, leaks, changes in EVA schedules, etc. (Jones, 2009-01-2493)

Why build complete models? It seems that such a model can shed light on general system-wide and detailed specific subsystem problems and so help make design, project, and program decisions. It can be used to gather, record, and communicate system information. It can be used to improve understanding, explore system behavior, size buffers, and test the effect of failure modes.

A general, all-inclusive life support model should bring out the important aspects of the system and show how they affect performance. However, developing a model to solve a specific problem may be a better approach. The goal of solving the problem can guide M&S. Rather than include everything, the model can be restricted to the processes relevant to the problem.

B. Problems that can be addressed by life support modeling and simulation

Some systems engineering problems are not suitable for modeling and simulation, but many are. A list of static and dynamic life support questions was developed and analyzed. “There appear to be five basic categories of questions. These are: steady state design, dynamic design, behavior during expected external events, impact and response to internal system failures, and impact and response to external off-nominal events.” (Jones, 2009-01-2493) The first category is static but the rest are dynamic, suitable for M&S.

The static design meets the steady state requirements. The dynamic design is implemented to smooth material flows and to control processes to maintain the system near its steady state design point. Dynamic design includes buffer sizing, processor rate margins, control systems, and operating procedures to maintain material flows and adjust process rates. Expected external events include resupply, EVA, and crew changeover, delay, and overlap. Internal life support system failures include processor down time and storage failures. External off-nominal events include delayed resupply, power failure, etc. (Jones, 2009-01-2493)

Other possible problems for M&S include; additional waste recycling, effects of ISRU (In-Situ Resource Utilization), alternate recycling system architectures, e.g., separate or combined condensate and urine processing, effects of changes between hydrated and dehydrated food, effects of start-up, shut-down, and quiescent waiting, solar cycle effects on power and operations timing, depressurization, and changes in crew number. Having on hand a general, all-inclusive life support model, or at least having the experience of developing one, would help is analyzing these problems, but most likely a further M&S more targeted development would be needed. If there is a specific problem, it seems that a direct analysis leading to a problem focused M&S would be the most efficient approach.

IV. Applying systems engineering to define best practices in modeling and simulation

A Department of Defense (DoD) sponsored study investigated the “Best Practices for Development of Models and Simulations.” (Morse et al., 2010). It identified a set of fifty modeling and simulation best practices and integrated them into a new simplified systems engineering framework.

To establish this framework, the study first identified the major systems engineering approaches in current use, including those developed by ISO/IEC, IEEE, ANSI, DoD, and INCOSE. These systems engineering approaches used the familiar systems engineering models: phased, waterfall, V-model, and spiral. These approaches were reviewed and used to synthesize a generic phased systems engineering framework, with five sequential time step phases and a sixth continuing management activity.

The major systems engineering phases are as follows:

1. Requirements development and validation
2. Conceptual analysis, system definition, and model development
3. Design synthesis, analysis, and verification
4. Establish model environment and develop product
5. Test, verify, and validate product
6. Project planning and management

An edited list of the identified best practices for modeling and simulation is provided according to these six system engineering activities.

1. Requirements development and validation
    - 1.1. Establish intent for model use
    - 1.2. Define the user and user needs
    - 1.3. Specify data content
    - 1.4. Use survey methods to elicit subject matter expert knowledge
2. Conceptual analysis, system definition, and model development
    - 2.1. Establish model focus by carefully choosing model behavioral aspects and data
        - 2.1.1. A good model must account for the behavior that is important to the problem
        - 2.1.2. A good model must provide ways of learning what it does and how it works
        - 2.1.3. A good model must need no more detailed information to run or to explain than the level of detail needed for the problem
    - 2.2. Select computer scientists with domain expertise to be on the conceptual modeling team
    - 2.3. Include full simulation specification including conceptual model limitations for the intended application
    - 2.4. Involve the decision maker in the model development process
3. Design synthesis, analysis, and verification

    - 3.1. Consider availability of data sources when designing the simulation
    - 3.2. Use intelligent analytical approaches to handle unavailable or unknown data
        - 3.2.1. Best estimates, likely maximum and minimum values, probability distributions, sensitivities and exploratory modeling
4. Establish model environment and develop product
    - 4.1. Establish the software development environment, including modeling frameworks (e.g., MATLAB)
    - 4.2. Design models as components with loose coupling
    - 4.3. Choose the right architecture definition tool
    - 4.4. Using identical random numbers for each successive simulation ensures that test conditions are replicated exactly between cases
5. Test, verify, and validate product
    - 5.1. Validate models against each intended use
6. Project planning and management
    - 6.1. Include user domain representatives and external developers in peer reviews
    - 6.2. Use subject matter experts throughout the development life cycle
    - 6.3. Use systems engineering analysis and documentation
    - 6.4. Document model abstraction decisions, models and simulation data (Morse et al., 2010)

Morse et al.'s objective was to "make Modeling and Simulations (M&S) a core enabler and integral element of systems engineering (SE)." They noted that the previous literature lacked detailed best practices for the development of models and simulations.

V. Some general principles of modeling and simulation

This section describes some general principles useful in modeling and simulation. It discusses some of the common M&S prescriptions made previously.

A. Find and involve a real customer

It is usual, as above, to assume that a paying customer exists and has clear fixed requirements. If this is so, two good M&S principles are, "Solicit inputs from the decision makers/customers of the model for the requirements specification." And, "Obtain concurrence with respect to the requirements specification by the decision makers makers/customers of the simulation project." (Pritsker et al., 1991)

Sometimes instead of a paying customer, there are several stakeholders. One possibility is that management is the paying sponsor, there are hypothetical but absent users who may be given the product or required to use it, and there are the developers who may be the only actual users. "In this case, the model is doomed – nobody is interested in the project." (Gibson et al., 2007, p. 302)

Management can fund M&S simply as a reasonable activity without a specific goal or defined project need. The best approach without a user customer might be for the management sponsor to assume the role of the customer, and develop and impose a good set of requirements. Without the strong focus provided by a paying user, it is hard to resist the temptation to assume away problems and avoid doing the harder parts of the model. The most useful M&S produces a real product that solves a real problem for a real customer.

B. Identify and solve a real problem

It is usual, as above, to assume that a paying customer exists and that he knows what his problem is. Then two good M&S principles are, "Models are associated with a set of questions." And, "The problem or problem statement is the primary controlling element in model-based problem solving." (Pritsker et al., 1991)

There are two interesting challenges here. First, "(The) client does not understand his own problem." (Gibson et al., 2007, p. 303) If the client did understand his problem, then he could solve it himself. And, "The original problem statement is too specific: you must generalize the problem to give it contextual integrity." (Gibson et al., 2007, p. 304) M&S is part of systems analysis, which is part of systems engineering, which is part of a planned or actual system development project. (Shishko, 1995, p. 71) The validity of a problem statement depends on how it fits into the broad context of accepted reality. The initial problem statement often implies a preferred solution. A good problem statement is based on an explicit shared view of reality and asks questions leading to further understanding of that reality. Discussion and iteration of the assumptions and problem statement is always useful.

C. Consider the assumptions and expectations of the sponsor

Why does management so often sponsor M&S developments? The sponsor probably does not intend to use the M&S, or he would provide strong user requirements. For example, the model would be required to be relevant, credible, transparent, and user friendly. (Shishko, 1995, p. 72) Most models are not asked to meet these specific requirements. Useful results would be traceable, explicable, and plausible. Again, most models are not asked to meet such requirements.

NASA life support M&S often does not suggest new approaches. It often assumes and explores the standard International Space Station (ISS) systems architecture and subsystems technologies, which date back to the 1960's. Formerly, food plants were more often included. NASA life support M&S often uses the long standard Equivalent System Mass (ESM) metric and avoids considering issues such as reliability and cost that could reveal problems in the ISS systems.

An important management tendency is to protect the status quo. It is difficult to sustain existing organizations, programs, and staff. This reduces management interest in drastic technological change and makes it easier to continue with the current life support approaches. Usually M&S is not asked to produce new concepts or challenge the current consensus.

It seems that this may be a case where, "(The) client does not understand his own problem." (Gibson et al., 2007, p. 303) The broad, overarching problem is how to provide life support for future missions that may have different requirements, constraints, and opportunities than ISS. M&S can create little new knowledge if it is focused on modeling current concepts. "The purpose of modeling is knowledge and understanding, not models." (Pritsker et al., 1991) Creating new knowledge requires challenging the conventional wisdom.

D. Challenge the conventional wisdom

The explicit purpose of some modeling efforts is not to produce new knowledge, but to defend the current consensus. This is called defensive or protective modeling.

In protective modeling, "Models are used to:

- Prove a point
- Keep assumptions hidden
- Use data selectively
- Support preconceptions and buttress preselected answers
- … and cover up the preselection
- Promote the authority of the (sponsor)." (Sterman, 2000, p. 858)

Creating new knowledge requires modeling that challenges current assumptions. This is unusual. It is called challenging or reflective modeling.

In reflective modeling, "Models are used to:

- Promote inquiry
- Expose hidden assumptions
- Motivate widest range of empirical tests
- Challenge preconceptions and support multiple viewpoints
- … and involve the widest community
- Promote the empowerment of the (users)." (Sterman, 2000, p. 858)

A modeling effort that successfully challenges the conventional wisdom produces new knowledge and understanding, possibly by generating previously unobserved or unrecognized dynamic behavior, or by discovering unanticipated process problems, or by suggesting alternate approaches.

E. Consider past work

There have been many M&S efforts in space life support that extend back more than thirty years. 29 of these are listed in the Appendix. Four NASA centers have produced models, as have three well known universities sponsored by NASA, and two NASA contractors. Government agencies and universities in Europe, Russia, and Japan have also produced life support M&S.

The strongest impression produced by this body of work is that any organization involved in developing recycling space life support finds it useful to develop its own M&S of life support. Creating and working with the M&S creates hands-on knowledge and understanding that could not be acquired by using someone else's model. The models are typically dynamic, providing time simulations of flows and stocks, but a few are static, simply computing total mass, power, etc. Many have food-producing plants and model closed ecosystems, but some include only physical/chemical recycling. Different software and modelling environments are used.

The specific recommendations for best practices and the general principles given here are based on the general modelling references. (Morse et al., 2010) (Pritsker et al., 1991) (Gibson et al., 2007) (Sterman, 2000) The concepts seem useful for life support M&S, but are not based on past life support efforts.

The power of M&S to focus on dynamic issues may narrow the system designers' vision. If a system is to be optimized, the model may consider only one goal, such as minimizing launch mass, or it may maximize a compound goal that makes simple continuous trade-offs. Effective system design should consider many conflicting and often incommensurable goals and risks that can not be included in a single M&S.

F. Define a good approach

No model can include everything. "All models are abstractions of reality." (Pritsker et al., 1991) Two important questions are what system level to model and how much detail to include.

It is necessary to have a top level system model to allow a system wide optimization. This avoids setting arbitrary constraints on the subsystems, such as mass or power budgets, that can lead to a suboptimal design. A different mass or power allocation may allow better performance. It is also useful to model all the alternate designs, to avoid eliminating alternates based on limited information, since this can also cause suboptimization. (Hazlerigg, 1996, p. 220)

It seems good to start with a simple model. Details can be added as needed. "Simpler models are easier to analyze in a timely and comprehensive manner." "The modeler should consider the use and construction of two models: a detailed and a simplified (rough cut) model." And, "Doubt may exist as to whether inclusion of a process in a model will affect the results." (Pritsker et al., 1991) "The most important thing to keep in mind when constructing a model is that one should not aim to capture the reality in all of its glorious complexity. … A good model should include only those processes that are critical to making predictions. … We begin by writing the simplest possible model and then sequentially add various candidate processes to it." (Turchin, 2003, p. 9).

A system is built to provide integrated, system level behavior The first model developed for a space life support system should be a system level, system wide model with the subsystems modeled as black boxes with defined input and output interfaces.

G. Be aware the limitations of modeling

"Models always embody assumptions about the real world they purport to represent, and they always leave something out." "There is often a significant difference between the substantive system cost-effectiveness issues and questions, and the questions that are mathematically tractable from a modeling perspective." (Shishko, 1995, p. 72) For example, minimizing launch mass or ESM is substituted for minimizing cost or triple redundancy is used instead of designing for the required reliability. Minimizing launch mass does not minimize mission cost. Adding redundancy does not always increase reliability.

"The universal computer model is a fantasy." "It is often the goal to develop the all-encompassing computer-based simulation system; however, repeated attempts have shown that an integrated system of multiple simulation types … is necessary." Gibson et al., 2007, p. 314)

H. Plan to develop several models

General top level, system models usually investigate only one or a few aspects of the system and so are inadequate for a complete analysis. "System effectiveness may, at best, have several irreducible dimensions." (Shishko, 1995, p. 73) "Typically, a collection of separate models is needed to provide all of these outcome variables." (Shishko, 1995, p. 71) "It is not unusual to have separate models to deal with costs and effectiveness, or to have a hierarchy of models - i.e., models to deal with lower level engineering issues that provide useful results to system-level mathematical models." (Shishko, 1995, p. 72)

Another reason to develop multiple models is that simulating the model will produce insight and generate further questions that require modeling. "The modeling process is evolutionary because the act of modeling reveals important information piecemeal." "The secret to being a good modeler is recognizing the need and having the ability to remodel." And, "Generality of understanding comes at the end of a modeling project; structure your modeling approach and modeling environment accordingly." (Pritsker et al., 1991)

VI. Conclusion

The modeling and simulation of space life support systems is necessary for understanding and is often done. The current life support system architecture was first defined and demonstrated with humans fifty years ago and has been continually investigated. The use of food producing, atmosphere recycling plants has also often been considered.

Repeated modeling of these familiar systems seems more useful in helping new investigators understand life support than in producing new insights.

In defining the life support system for a new mission, modeling and simulation systems is useful but not sufficient. A top-down systems engineering approach, starting with the requirements, developing alternate systems, and comparing them according to multiple criteria seems necessary. Solving specific Modeling and simulation problems would be an important part of the system definition.

Appendix: Modeling and simulation work

Table A.1 lists past life support modeling and simulation efforts. The table includes references, locations where the work was done, the name of the simulation effort if any, and brief notes describing the effort.

Table A.1. Past life support modeling and simulation efforts.

#	Reference	Location	Name	Notes
1	(Averner, 1981)	NASA ARC		Plants
2	(Stahr et al, 1982) (Babcock et al., 1984)	UC Berkeley NSCORT		Plants, control strategies, failures
3	(Rummel and Volk, 1986)	NASA ARC	BLSS model	Bioregenerative life support
4	(Cullingford, 1989)	NASA JPL	CELSS emulator	Plants
5	(Rudokas et al., 1989)	NASA ARC	DAWN	Physical-chemical life support, expert systems
6	(Bacskay and Knox, 1989)	NASA MSFC		ISS air system
7	(Seshan et al., 1989) (Seshan et al., 1991) Ferrall et al., 1995)	NASA JPL	LISSA	Mass, power, open loop versus regenerative
8	(Schwartzkopf and Cobb, 1990)	Lockheed		Life support systems design
9	(Gustavino et al., 1990)	McDonnell Douglas		Lunar base
10	(Kolodney et al., 1991)	NASA JSC		Plants and air system
11	(Kurmazenko et al., 1992)	NIICHIMMASH, Moscow	IRLSS model	Regenerable life support
12	(Drysdale et al., 1992) (Drysdale, 1997)	NASA KSC	OCAM	Object-oriented CELSS Analysis and Modeling
13	(DaLee and Lee, 1993)	McDonnell Douglas		Expert system ECLSS trade tool
14	(Suzuki et al., 1994)	McDonnell Douglas, Shimizu		Model for systems analysis
15	(Osburg et al., 1998) (Detrell et al., 2011)	ESA	MELiSSA	Graphical simulation
16	(Finn, 1999) (Jones et al., 2001)	NASA ARC		Dynamic models, trade studies
17	(Fleisher et al., 1999) (Goudarzi and Ting, 1999) (Rodriguez et al., 2003)	Rutgers NSCORT	BPM	Object oriented biomass production simulation
18	(McGlothlin et al., 1999) (Yeh et al., 2001) (Yeh et al., 2004) (Yeh et al., 2009)	NASA JSC	ALSSAT	Static, system sizing, launch mass
19	(Pérez Vara et al., 2003) (Rueda et al., 2010)	ESA	EcosimPro	Object oriented, differential equation, multidisciplinary model
20	(Kortenkamp and Bell, 2003) (Manders et al., 2005) (Rodriguez et al., 2007)	NASA JSC	BioSim	Multi scale continuous-discrete model, controls
21	(Aydogan et al., 2004) (Aydogan-Cremaschi et al., 2009)	Purdue NSCORT	SIMOPT	Simulation with deterministic optimization

22	(Arai et al., 2008)	MIT		Educational
23	(Miyajima, 2009)	Tokyo Jogakkan college		Designer-tool interaction
24	(Czupalla et al., 2010) (Czupalla et al., 2011) (Putz et al., 2016) (Schnaitmann and Weber, 2016)	Technical University of Munich	V-HAB	Dynamic multilevel mission simulation
25	(Detrell Domingo et al., 2011)	University of Stuttgart	ELISSA	Reliability analysis
26	(Allada et al., 2012)	NASA JSC		Processor simulations
27	(Schubert et al., 2014)	ESA (MELiSSA Group)	SCALISS	Scaling biological life support
28	(Do et al., 2015)	MIT	HabNet	Habitation, supportability, failures, spares
29	(Chambliss et al., 2015) (Chambliss et al., 2016)	NASA JSC		Water tracking model

Of the 29 M&S efforts, 16 have been given names. Most of the 29 seem to be designed as tools to be used in solving a general class of problems involving alternate subsystems or different missions. The M&S work listed extends over 36 years, and several individual efforts have continued for more than ten years.

Of the 29 M&DS efforts listed, 20 were done by NASA. Thirteen were done at four NASA centers, ARC, JPL, JSC, and MSFC, three were done by universities under a NASA sponsored NSCORT, and four by Lockheed and McDonnell Douglas under NASA contracts. Of the nine non-NASA efforts, three were done by ESA and two by MIT. One each was done by NIICHIMMASH, Tokyo Jogakkan college, Technical University of Munich, and University of Stuttgart. It seems that most organizations with an interest in designing space life support have developed their own M&S model. A few have been encouraged to adopt the NASA ALSSAT model, which computes total launch mass for system trade-offs and is not a dynamic simulation.

Most life support M&S is concerned with dynamics, including flows, controls, logistics, and buffer sizing. Some specific simulations include failure effects and responses. Others consider subsystem reliability and spares. Static models compare the launch mass of open loop resupply with that of recycling systems.

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