EXECUTIVE SUMMARY

Advanced Mission Operations Concepts & Technologies for Future ESA Missions

Booz & Company B.V.
Apollolaan 151
Minerva Building
5th Floor
1077 AR Amsterdam
The Netherlands
Tel +31 20 504 1900
Fax +31 20 504 1990
www.booz.com

Table of Contents

Figures

Tables

1 Introduction

This executive summary provides an overview of the Advanced Mission Operations Concepts & Technologies for Future ESA Missions study conducted by Booz and Company and the Albert-Ludwigs-Universität Freiburg Autonomous Intelligent System (AIS) Lab and the Foundations of Artificial Intelligence Lab.

Based on the suite of future ESA missions, this six month study provides ESA with two major findings. The first, is a set of mission operations requirements categorized by tasks and whether they are implemented on-board or on the ground and a set of new and innovative operations concepts for ESA to consider. The second is an artificial intelligence and automation technology survey of current technologies being used across industry not limited to space, reviewed according to criteria provided by ESA to develop a technology roadmap until 2015. To add more value to the technology roadmap, three mission specific roadmaps were developed to support the ESA *Cross Scale Mission* and a *Lunar Manned Moon Rover Mission*. These tactical roadmaps were developed supporting the effective and efficient introduction of the identified technologies in the mission operations environment.

Figure 1-1 provides an overview of the study implementation, showing the major objectives for each phase and the results that were achieved.

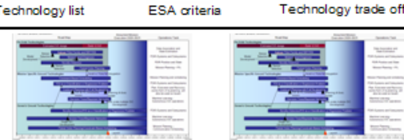
	Objectives	Result
Survey Future Missions	• Derive a set of requirements for the suite of future ESA missions. • Organize requirements based on high level mission tasks like planning, FDIR etc.	• High level mission Survey, including Objectives, readiness Launch date etc. 
Define Mission Requirements	• Overall Mission requirements developed based on specific operations areas.	• Mission Planning & Scheduling, Planning, Execution & Re-planning, Monitoring & Control, AOCS & Navigation, DMS, EPS, TCS. TT&C, Ground Resource Management, FDIR, On-board vs Ground Requirements, Data Management.
Develop Operations Concepts	• Develop operations concepts which would satisfy the requirements developed for future ESA missions.	• Outlined ESA used and new operations concepts: Dimmed Lights, Lights out, Distributed, Service Oriented, Family of Missions.
Survey Technologies	• Surveyed existing technologies in artificial intelligence and automation.	• Over 80 technologies surveyed, all with a readiness state to have been at a least prototyped.
Perform Technology Trade off	• ESA selected trade off criteria (cost, risk, ops impact etc). • Each technology was evaluated against the criteria.	 Technology list / ESA criteria / Technology trade off results
Develop Roadmap per mission	• Determine appropriate ops concept. • Develop roadmap based on selected technologies and ops concept requirements.	

Figure 1-1: Study Evolution

2 Study Overview

Figure 2-1 shows the study logic. Following an initial fact finding exercise a set of mission requirements categories were identified and a set of innovative operations concepts were developed. At this point ESA, was asked to provide the 5 criteria they deemed most important in future technologies, which formed the basis of a technology trade-off performed in the second half of this study.

In the second part of this study the University of Freiburg performed a survey of current automation and robotics technologies and evaluated their readiness against the set of criteria defined by ESA (cost, TRL etc). By performing this technology trade-off based on ESA criteria, the technologies most interesting to the future suite of ESA missions were identified. Then, the identified technologies were linked to the various mission requirements and operations concepts to develop a high level technology roadmap. To further add value to this study a final tailoring of the technology roadmap and trade-off was performed to match two specific ESA missions, Cross Scale and Lunar Rover and Mapper.

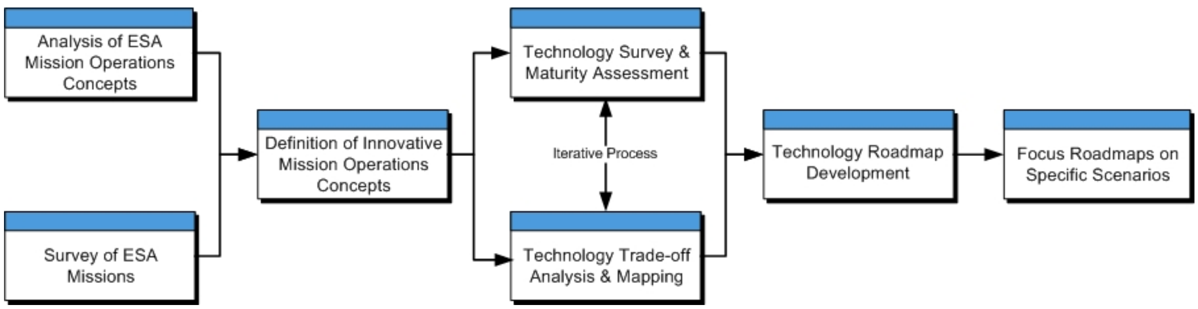


Figure 2-1: Study Logic

2.1 Future ESA Missions Overview

In order to develop advanced operations concepts that will satisfy the demands of future European Space Agency (ESA) missions, it was necessary to identify and prioritise the main requirements that are driving the spacecraft design and the operations definition. The ESA missions shown in Figure 2-2 were included in this phase of the study. Missions depicted in light green are already in operations while those in light blue are currently planned; the missions depicted in yellow are in early definition stages.

Research was conducted to identify and categorise the main drivers, requirements and technology areas that influence the spacecraft design and the mission definition and implementation. In order to better scope this task within the overall effort necessary for the study, four main focus areas were identified for each mission family:

- Orbital requirements
- Spacecraft requirements
- Payload requirements
- Ground Segment requirements
- Ground Operations requirements
- Manned Missions requirements

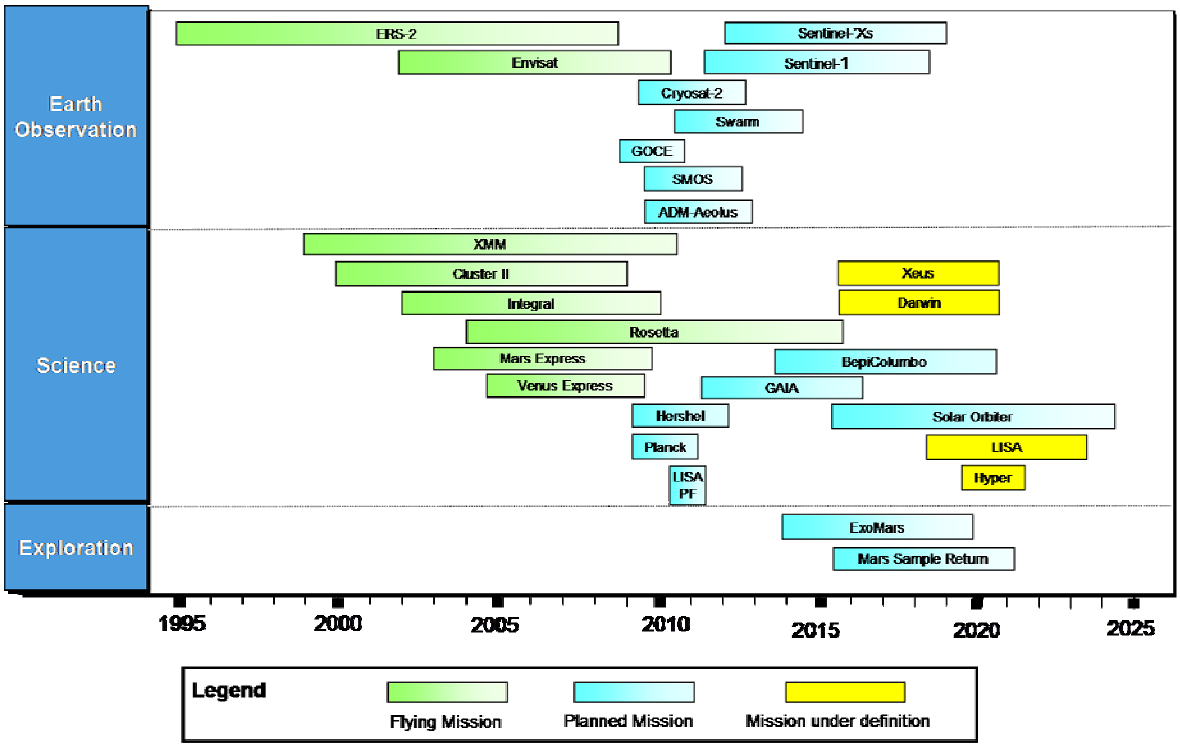


Figure 2-2 : ESA Missions Overview

2.2 Operations Concepts

Once the main drivers that can potentially affect the spacecraft design and the definition of the related operations concepts were identified, it was possible to critically review the operations concepts that are being developed by ESA and develop new concepts based on an overall mission complement perspective. The following concepts were described and reviewed in the study:

- Family of Missions Concept
- Dimmed Lights Concept
- Lights-Out Concept
- Distributed Operations
- Service Oriented Operations.

These operations concepts, some of which are not being actively pursued or studied by ESA, are described hereafter.

2.2.1 Family of Missions Concept

The principle of the "family of missions" operations concept refers to sharing as many elements as possible between two or more missions in order to utilise the available resources in the best possible way and to reduce costs. Common areas include Ground segment elements (i.e. Stations, Interfaces, Mission Control System (MCS), simulators, tools, etc.), Facilities (i.e. control rooms), teams and processes and methodologies.

Booz & Company Proprietary

2.2.2 Lights-Out Concept

Lights-Out, operations refers to automated operations without the immediate presence of an operator. The system is designed to run autonomously up to the point where a human expert will be needed to deal with unforeseen problems (anomalies) that are outside the scope of the autonomous capabilities.

2.2.3 Dimmed Lights Concept

The Dimmed Lights concept is a "lighter" implementation of the Lights-Out operations concept which foresees the manning of the control rooms for a limited amount of time (e.g. normal office hours), while the mission schedule controls the activities the rest of the time. In case of anomalies, the data can be made available to operators located within and outside the control centre for analysis and for decision making.

2.2.4 Distributed Operations

The distributed operations concept contemplates operations that are carried out by various control teams and users operating from a disparate set of facilities. This setup has a major advantage in that there is no need to have dedicated facilities (i.e. control rooms, user centres, etc.). The spacecraft and payload operations can be run using a common set of web based tools (i.e. mission control system, planning system, ops support tools, etc.) from workstations placed in offices, universities and labs, with a sizable reduction in costs.

2.2.5 Service Oriented Operations

Service oriented operations are based on the possibility of providing direct access to a particular payload/mission to potential users, in the form of pre-defined "services". This would allow a user to only request a certain service for a specific time period, with all that is in between being fully transparent.

This concept could also be applied to a multi-mission ground segment with the latter providing a catalogue of generic services that a mission could request, including all relevant information regarding quantity and quality of service provision, means of evaluating the service, as well as a list of references describing the constraints, requirements and interfaces to be implemented.

2.3 ESA Defined Technology Trade-off Criteria

High level trade-off criteria were selected by ESA, and then each criterion was broken down into quantifiable measures to facilitate comparison between technologies. Additionally, ESA provided a prerequisite which was used to determine whether a particular technology should be included in the trade-off analysis or not.

2.3.1 ESA Requested Pre-Requisite

In order to avoid dedicated technology developments, this study only considered technologies that were already being used in other industries or were sufficiently mature to have been tested as laboratory prototypes. This pre-requisite also ensured that the identified technologies were 'in sync' with those used in other industries, avoiding technologies that would require high customization or would be a one off development.

Booz & Company Proprietary

2.3.2 ESA Provided Trade-off Criteria

Table 2-1 provides an overview of the technology trade-off criteria (in no particular order of priority) that ESA selected from the original list that was provided.

Criteria	Description
Compliance/ Criticality	The criticality criterion is used to assess how important a function/element is to be implemented is in order to achieve the mission goals. The criterion is also used to re-assess the mission objectives in the case of a reduced requirements scenario.
Maturity	Without being constrained by the exactness of ESA's Technology Readiness Level (TRL) definitions, maturity is used as a proxy measure of the technology readiness and is used to assess the development level of evolving technologies before they can be introduced into an operational system or environment. Therefore the ESA TRL ranking was modified to be more generic and represent maturity across multiple industries rather than focusing on space.
Complexity/ Simplicity	The complexity of a function is directly related to the criticality and the reliability. Complexity will have an impact on cost and size/weight and might even affect the reliability of the system.
Cost	Cost (together with reliability) is a major criteria in deciding whether a technology can be implemented or not.
Risk	Risk indicates the potential negative impact to the operational environment that may arise from the introduction of a new technology. It addresses cost, schedule and technical performance. Programmatic and political risks are not included. ▸ Cost slip ▸ Redesign ▸ Schedule ▸ Reliability impact ▸ Supportability
Operational Impact	The operational impact is used to assess the effectiveness of a particular technology within the operational objectives. This criterion is measured based on the extent to which the technology satisfies the requirements.

Table 2-1: Trade off criteria description

2.4 Technology Survey

A general survey of state of the art technologies in automation, artificial intelligence and robotics not limited to those currently being applied to space was performed. Additionally, some commercial off the shelf (COTS) tools with embedded advanced technology dedicated to space operations were identified. Following this, a general assessment and preliminary mapping of the proposed technologies was performed as an iterative process. Lastly each technology was evaluated against the ESA provided trade-off criteria (See Figure 2-3) and the most suitable technologies for a particular operations task were identified.

Booz & Company Proprietary

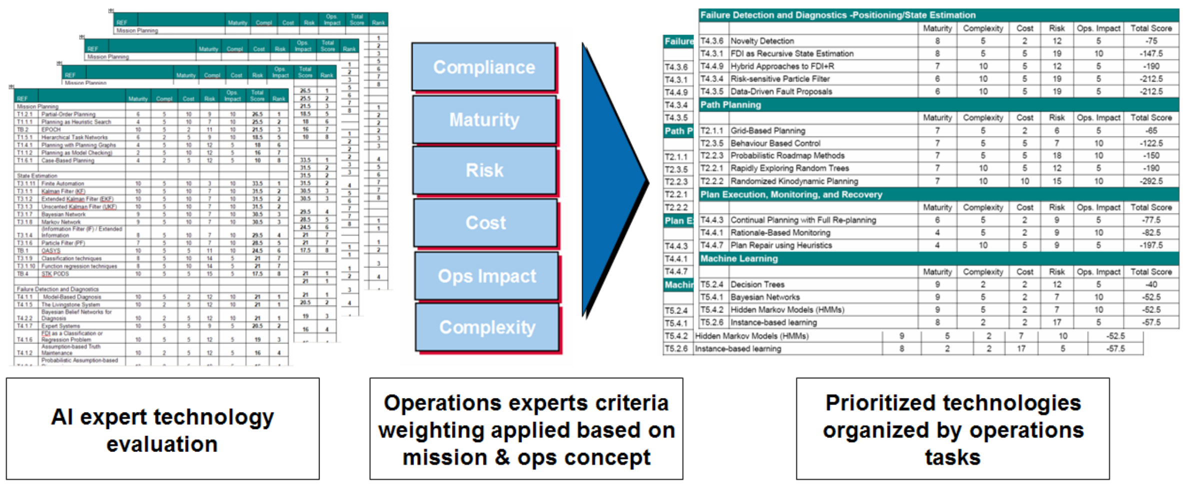


Figure 2-3: Technologies Trade-off Evaluation Process

Table 2-2 provides a sample of the areas of AI technologies, with a potential relevance for space missions, that were investigated. These were mapped against the operational requirements identified in the earlier parts of the study.

High AI task	AI Technology area
Symbolic Planning and Scheduling	State Space Search Plan Space Search Problem Reduction Planning Graphs Hierarchical Planning Case-Based Planning Integration of Planning and Scheduling Constraint-based Scheduling
Path Planning	Discrete Approaches Grid-Based Planning Sampling-Based Approaches Predictive Roadmaps Other Approaches
State Estimation and Tracking	Filter Techniques Kalman Filter Data Association Bayesian Network Markov Network
Monitoring and Recovery	Fault Detection and Diagnosis Model-Based Diagnosis Model-based Diagnosis with Temporal Constraints Expert Systems Probabilistic Approaches Probabilistic Assumption-based Diagnosis Fault Detection in Dynamic Domains Plan Monitoring, Re-planning, and Recovery Rationale-Based Monitoring Optimality Monitoring

High AI task	AI Technology area
	Continual Planning with Full Re-planning
Machine Learning	Function Approximation Supervised Learning Unsupervised Learning Graphical Models Reinforcement Learning

Table 2-2: Investigated Technology Areas

The Albert-Ludwigs-Universität Freiburg conducted the individual technology evaluation, which was then further processed by our experts by applying a set of "weights" based on the mission operations requirements and concepts. This resulted in a prioritised list similar the one provided in Table 2-3.

Tab-01: Mission Planning and Scheduling	Pre-Requisite	Maturity	Complexity	Cost	Risk	Operational Impact
T1.1.1 (Planning as Heuristic Search)	X	3	High	Low	16 (3+3+10)	High
T1.1.2 (Planning as Model Checking)	–	–	–	–	–	–
T1.2.1 (Partial-Order Planning)	X	3	High	Low	16 (3+3+10)	High
T1.3.1 (Planning as Satisfiability)	–	–	–	–	–	–
T1.4.1 (Planning with Planning Graphs)	–	–	–	–	–	–
T1.5.1 (Hierarchical Task Networks)	X	3	High	Med	16 (3+3+10)	Partial
T1.5.2 (Search in the Abstraction Space)	–	–	–	–	–	–
T1.6.1 (Case-Based Planning)	X	3	High	Med	20 (5+5+10)	Partial
T1.7.1 (Iterative Waterfall Integration)	X	3	Low	Low	10 (1+4+5)	Partial
T1.7.2 (Adaption of Resource Intensity Estimates)	–	–	–	–	–	–
T1.8.1 (Constraint-based Scheduling)	X	3	High	Low	20 (5+5+10)	High
T1.8.2 (Earliest Start Time Approach)	–	–	–	–	–	–
T1.8.3 (Resource Envelope)	–	–	–	–	–	–
T1.8.4 (Conflict Selection Heuristics)	–	–	–	–	–	–
T1.8.5 (Other Approaches)	–	–	–	–	–	–

Table 2-3: Sample Technology Trade-off

3 Study Findings

3.1 Technology in Support of Operation Concepts

The definition of the operation's concept is a major step in defining a mission and its requirements. In a classical mission development approach, one can identify:

- The Mission Objectives, which provide the overall mission scope.
- The Mission Requirements, which provide a set of high level requirements (e.g. number of spacecraft, availability, mean response time, ground response times, data return percentage, data quality percentage, timeliness, etc.). These requirements are generally split into three broad areas and are classified as follows:
  - Functional Requirements;
  - Operational Requirements;
  - Constraints.
- The Operations Concepts, which then drives the implementation of both on-board and on the ground systems, keeping in mind the defined high level requirements and constraints.

Each operations concept is characterised by specific needs, some of which are listed in Table 3-1.

Operations Concept	Fundamental requirement
Family of Missions	• Commonality between spacecraft systems and mission characteristics. • Plan-driven operations. • Some degree of on-board automation.
Dimmed lights	• High levels of on-board and ground automation. • Plan-driven operations. • Situational awareness.
Lights Out	• High level of on-board and ground automation. • Sophisticated mission planning system with execution monitoring and repair. • Situational awareness.
Distributed Operations	• Hierarchical definition of the ground segment elements (e.g. the MCS). • Security • Sophisticated mission planning system to optimise the resources usage.
Service Oriented Operations	• Sophisticated mission planning system to optimise the resources usage. • Security. • Hierarchically implemented ground systems.

Table 3-1: Fundamental Requirements for each Operations Concept

The process normally used for defining such concepts and the related architectures and for identifying the best solution is described in Figure 3-1. This is an iterative process where a number of possible implementations are defined and then evaluated according to a set of criteria (e.g. feasibility, cost, risk, etc.) to come to the final choice.

Booz & Company Proprietary

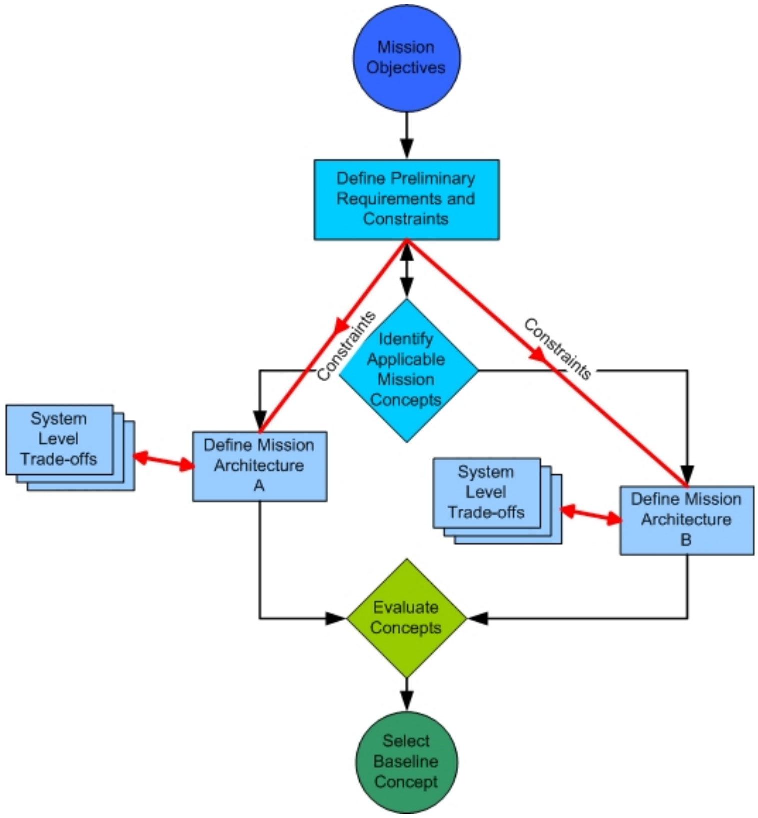


Figure 3-1: Mission Definition Process

This simplified view (adapted from the Space Missions Analysis and Design book from W.J. Larson and J.R. Wertz) highlights how several concepts can be identified and how these are reflected in possible systems architectures, which are then evaluated using the requirements and constraints identified to come to a selection for implementation.

The type of operations concept chosen for a mission will contribute to the definition of the level of automation, both on-board and on the ground, required to run the mission. The areas that are going to affected the most are:

- Automation including FDIR (both on-board and on the ground).
- Mission Planning and Schedule execution.
- Schedule monitoring and repair.

Mission Planning and Mission Automation are closely related and can have a major impact on the infrastructure and manpower requirements. In order to reduce human interactions, activities can be pre-planned and executed autonomously by the spacecraft and/or the ground infrastructure, and intelligent planning systems can manage the available resources in a more efficient way and can help in increasing the scientific return of a mission.

The application of these technologies is not limited to the space segment only, but can also help in dealing with the increased complexity and distribution of the ground segments. The introduction of new standards (e.g. SOA, SLE, etc.) allows the use of external infrastructure to support a mission and the increased complexity will require either an increase of personnel or an increase of the automation level of the infrastructure.

The introduction of automated, advanced technology systems will have a high initial procurement cost, which will be eventually offset by their increased usage and standardisation. On the other hand, these systems allow lower long-term operational costs (and therefore lower overall costs) thanks to the reduced infrastructure and manpower costs required as depicted in Figure 3-2.

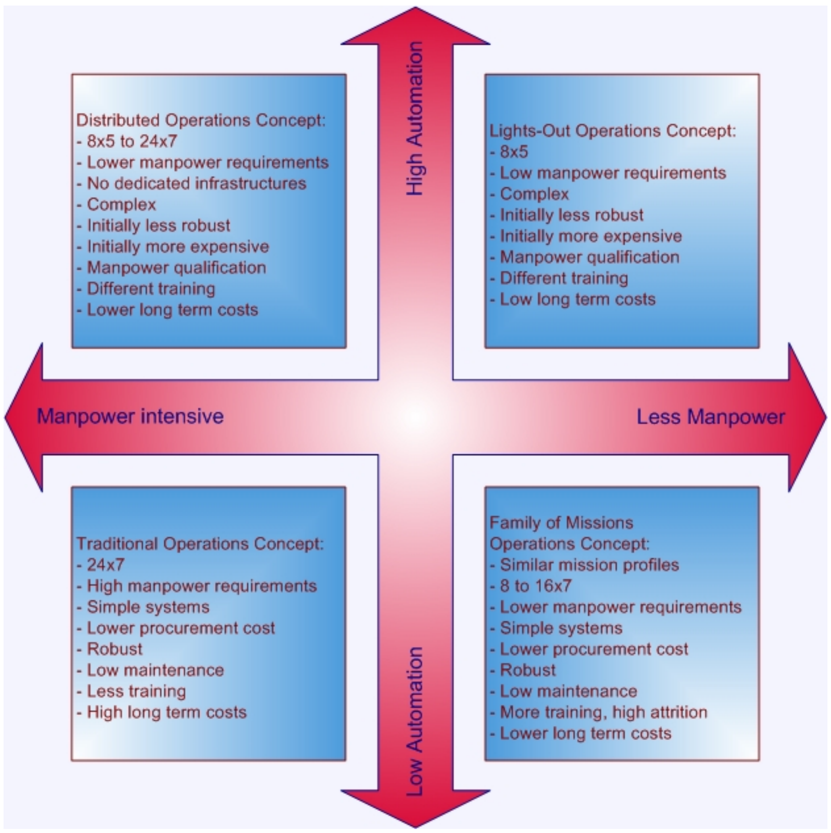


Figure 3-2: Technology Long Term Effects

3.2 Managing the Introduction of New Technology

The introduction of newer or more advanced technology is always associated with some form of change and should follow and appropriate change management approach in the organisation. This can go from a simple change of attitude toward the machine, to process updates and finally to major re-definition of the human/machine interactions. It is likely that the most difficult change will be the cultural change required to accept these new systems.

No matter how much advanced technology plays a role in everyday life, the operations environment is very traditional and safety oriented, and is therefore rather resistant to changes. The introduction of newer, intelligent technologies must be carefully managed in order to prevent any mishaps that might negatively influence the evolution of the operations models. This complex transition could be difficult, but it can be managed using the experience accumulated in other sectors (e.g. civil aviation, manufacturing, automotive industry, etc.) where more advanced technologies and automation have already been successfully integrated into the working environment. This approach can be further enhanced by identifying potential "quick wins" projects (see Figure 3-3) that would help establishing a positive attitude toward the new technologies. These can then be followed by more challenging projects which will bring longer term benefits, but which are also connected to more far reaching changes.

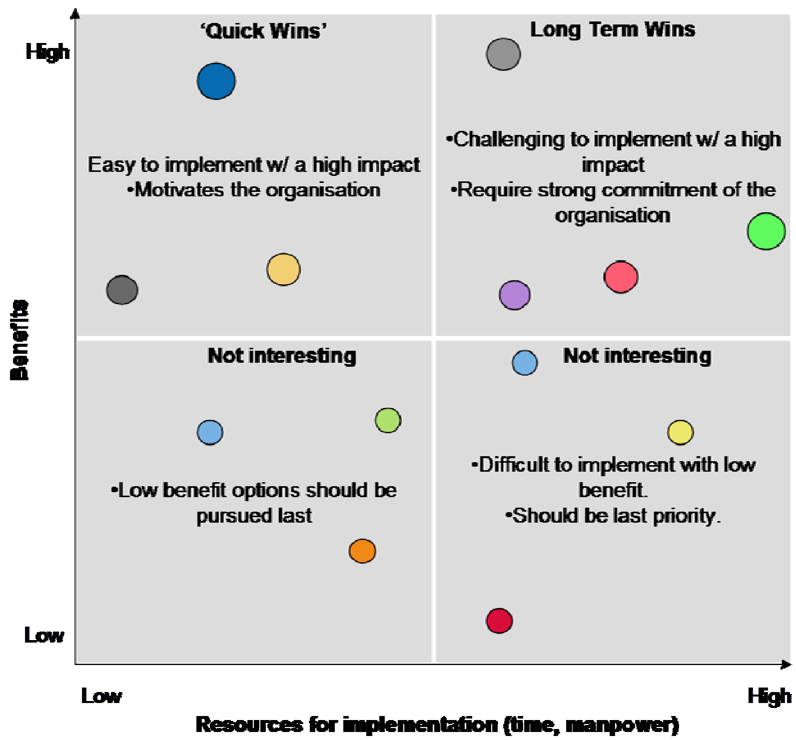


Figure 3-3: Development Approach – Quick vs. Long-term Wins

The introduction of advanced technologies will directly affect a number of areas (e.g. knowledge retention, active awareness, man/machine interfaces, etc. – see Table 3-2), but this could be managed by implementing new management and training concepts similar to those that have been developed for the civil aviation with the introduction of sophisticated and autonomous systems in the aircraft cockpits (Crew Resource Management).

The introduction of new operations concepts and technologies will also have an impact on the composition of the operations teams. These will generally be smaller and will require a different mix of personnel other than those currently identified (i.e. Spacecraft Controller, Spacecraft Analyst, System Engineer, etc.). These new professional profiles will have different skill level requirements, which will have an impact on recruitment and training.

As a consequence, an area that will most likely require significant change is training. This will change in its nature and its level will increase together with the level of complexity of the implemented systems. The training will also require tailoring to address the specific mission requirements/scenario and the technologies being introduced, and different methods (e.g. computer based training, hands-on training, high fidelity simulations, etc.) will allow for a smoother introduction of these changes.

Booz & Company Proprietary

Area	Impact
Operational Culture	People need to accept the increased role of the machines in the loop. The use of "quick wins" projects can help motivate people and accept the changes.
Situational Awareness	It is necessary to implement a process by which it will be possible to retain the necessary situational awareness to allow an operator to take over the control.
Knowledge Retention	If more activities are automated, then the related knowledge might be lost.
Man-Machine Interface	The interface between the systems and the operators needs to be as simple and intuitive as possible to reduce the risk of errors.
Job Complexity	More complex systems will require a change in the job profile and entry requirements.
Training	The increased complexity of the systems will require different types and levels of training.

Table 3-2: Technology Impact Areas

All these changes will initially be associated to two other factors, namely risk and cost. The former will again depend on the level of integration of the technologies within the operational environment and on the level of trust they are given by the teams. The best approach to mitigate this risk is to use an evolutionary approach, giving enough time to the operations teams to learn to work with the new systems and to the systems themselves to reach the necessary level of maturity. The latter, will depend on the technology that it is being used to implement a concept, its level of maturity and by the level of complexity (e.g. reliability) that is required. One has to accept the fact that introducing new technologies will always be associated with an initial longer lead time (until the system is mature enough to be used by several missions) and a higher initial cost, but it must also be compared with what it would cost to maintain a full operations team and infrastructure for a mission with five to ten year duration.

3.3 Technology Roadmaps

Based on the technology trade-off exercise and an analysis of the missions, a technology roadmap was developed for each mission requested by ESA. A sample of the Cross Scale mission roadmap is provided section 3.1 below, the roadmap is divided into three rows:

- On-orbit Technologies – This row provides a roadmap for technologies that should be included in the flight hardware (including software).
- Mission Specific on ground technologies – This row provides a roadmap for technologies that require highly specific tailoring to the mission/flight hardware, but that remain part of the ground infrastructure.
- Generic Ground Technologies – This row provides a roadmap for technologies that could be implemented in the ground infrastructure but can be generically used in several missions.

The selection of technologies supports an operations concept based on a combination of reduced manning and widely distributed user community (e.g. Dimmed Lights and Distributed Operations).

Each mission roadmap had an estimated mission flight date and end date which was used as a major milestone for the technology implementations. Furthermore, the best suited technologies for

Booz & Company Proprietary

each operations task were provided in the roadmap along with major milestones suggested to implement the technologies.

It is not recommended to implement all new technologies identified for each mission, as the collective risk of this effort is significant. ESA should consider each technology individually and then the collective risk to the ground segment and specific mission of the potential suite of innovative technologies.

3.3.1 Sample Roadmap - Cross-Scale Mission

The Cross Scale mission technology roadmap is provided in Figure 3-4. This map is based on the trade-off performed in this study, combined with knowledge of the current ground segment state at ESOC. Path planning is not required for this mission and thus is not included in the roadmap.

A number of technologies appear to be promising, but one has also to consider the amount of time they will require to reach the necessary maturity and the operational impact they will have.

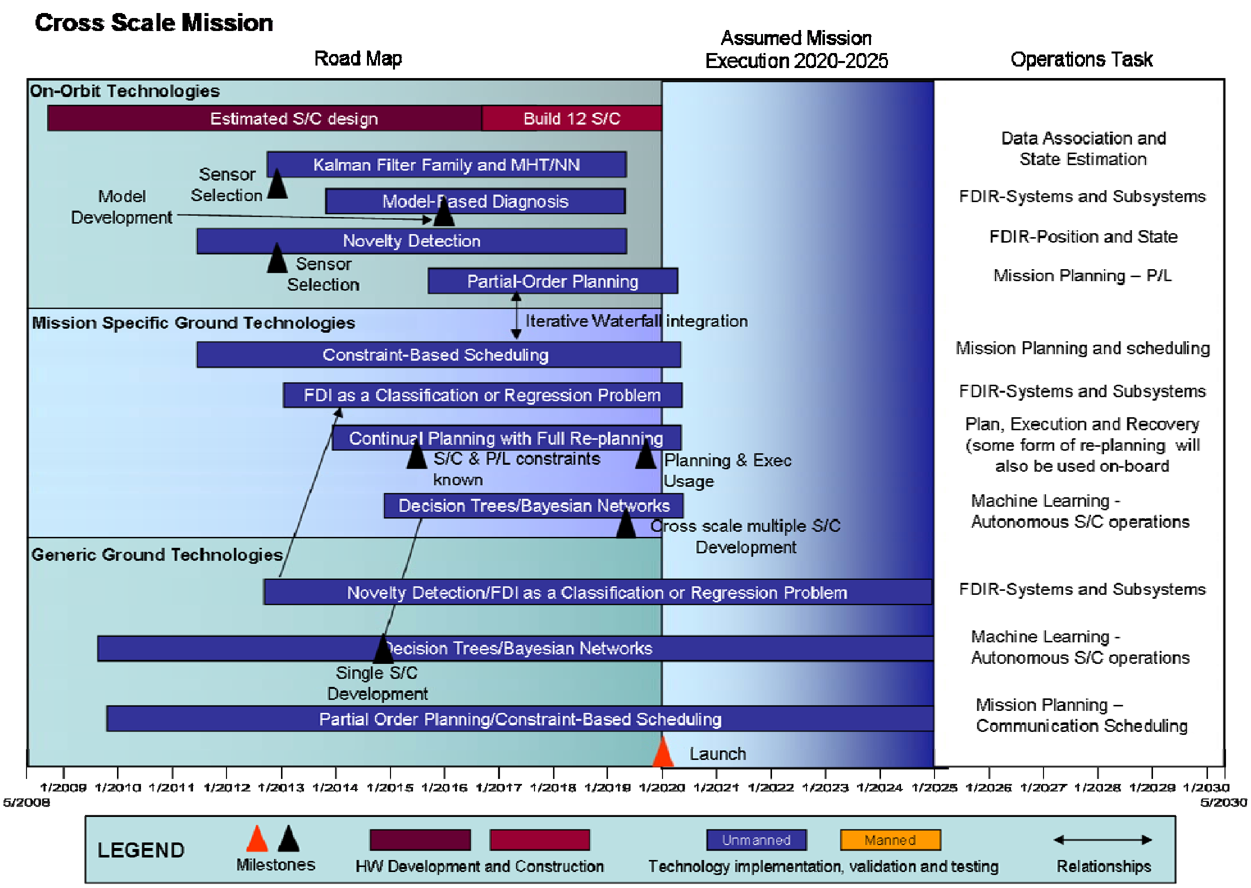


Figure 3-4: Sample operations technologies roadmap - Cross Scale Mission

4 Study Recommendations

Based on the results of the technology trade-off and mapping, recommendations were made on major operations tasks and which technologies should be pursued related to these tasks. Recommendations were made on the following areas of AI technologies related to space mission operations.

- Planning / Scheduling: We recommend to investigate planning based on Hierarchical Task Networks (HTNs) and Case-Based Planning as semi-automated techniques, and Planning as Heuristic Search, which is less efficient, for cases in which fully automated techniques are necessary.

- Plan Execution, Monitoring: The most straightforward way to deal with uncertainty and failure during plan execution is to use Full Re-planning in the case of plan failure. Plan Repair Using Heuristics would be a less mature alternative strategy.

- State Estimation: Although the choice of the underlying algorithm is highly dependent on the sensor and the modelling of the system dynamics, we highly encourage to investigate Kalman-Filter related techniques (KF/EKF/UKF/IF/EIF) in the beginning.

- Failure Detection / Diagnostics, System: The classic approach of Model-Based Diagnosis can be applied when the system model is discrete, fully known, and the noise rates are low. In particular, the Livingstone System has been used successfully in previous space missions. Also, expert systems are an often-applied technique for selecting actions as a response to certain failure states.

- Failure Detection/Diagnostics, State Estimation: For low dimensional processes, the problem is typically approached as a Recursive State Estimation problem, often with a hybrid component. If the failure states are not modelled explicitly, typical approaches try to classify the residual error of state estimation algorithms (Classification and Regression and Novelty Detection)

- Path Planning: Path planning and control is typically realized in a hierarchical manner. On the higher level, Probabilistic Roadmaps or Grid-Based methods find a *rough* outline of the trajectory which is then realized using Behaviour-Based Control or methods based on Potential Fields on the lower system level. Field D* and Dynamic A* are prominent examples of methods that deal with dynamic environments (e.g. other agents moving).

- Machine Learning: On the lower level Instance-Based Learning techniques appear promising, whereas Decision Trees and Expert Systems are often used in discrete domains, and Non-Parametric Regression in continuous ones.

Booz & Company Proprietary

5 Technology Prototyping

The final part of this study provided an initial indication of when and with which mission the most promising technologies could be used as demonstrators/prototypes based on the current best knowledge and complexity of the identified missions.

For example, this analysis concluded that the planning and scheduling technologies could be tested with any mission available at the time they become available/mature. The prototype would run in parallel with the nominal system and the results would be compared. HTNs, Case-Based planning and Constraint-Based scheduling, integrated in an Iterative Waterfall manner, could be already tested in the next 4 to 6 years; simpler models could be used even earlier. Partial-Order planning and planning as Heuristic Search will require more time, probably between 6 and 8 years, depending on the complexity of the mission.

Figure 5-1 provides an overview of the complete technology prototyping results and hence an indication of the number of years it might take some of the identified technologies to reach a level of maturity that would allow the implementation of complex systems. Those technologies that have no projection are already considered mature. The more complex the implementation, the longer it will require, thus the initial implementation of simpler prototypes should be considered for validating the technologies.

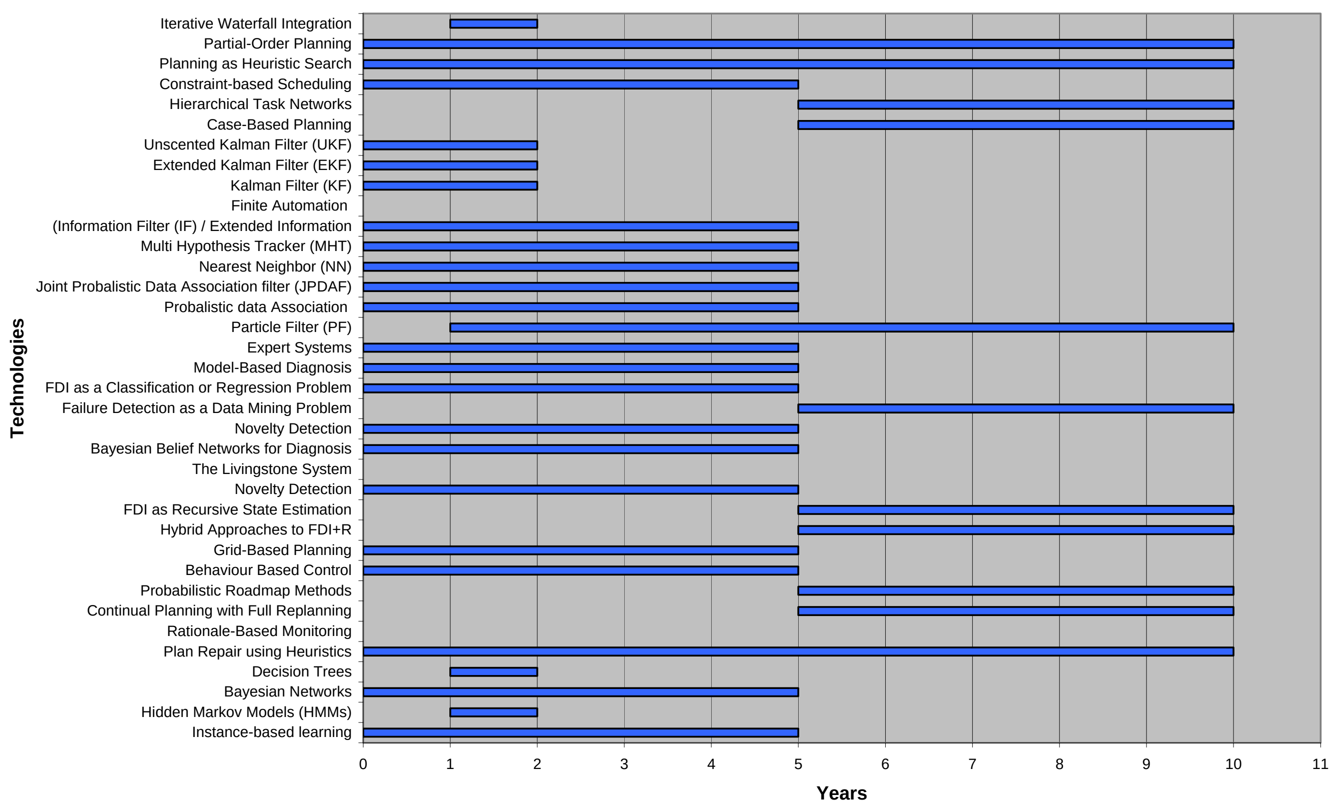


Figure 5-1: Technologies prototyping maturity projections

Booz & Company Proprietary

APPENDIX A Acronym List

AI	Artificial Intelligence
AIS	Autonomous Intelligent System
BAH	Booz Allen Hamilton
CBT	Computer Based Training
CCD	Charge Coupled Device
COTS	Commercial Off The Shelf
EO	Earth Observation
ESA	European Space Agency
ESOC	European Spacecraft Operations Centre
ESTRACK	ESA distributed ground network of antennas
FDIR	Failure Detection Isolation and Recovery
GSFC	Goddard Space Flight Center
ICD	Interface Control Document
JPL	Jet Propulsion Laboratory
KO	Kick Off
LOS	Loss of Signal
MCS	Mission Control System
MOIS	Manufacturing and Operations Information System
MUST	Mission Utility & Support Tools
S/C	Spacecraft
SLAM	Simultaneous Localisation and Mapping
SOW	Statement of Work
SME	Subject Matter Expert
TRL	Technology Readiness Level
WBS	Work Breakdown Structure
WPD	Work Package Description
UF	Albert-Ludwigs-Universität Freiburg

Booz & Company Proprietary