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ENGINEERING PLANETARY EXPLORATION SYSTEMS: INTEGRATING NOVEL TECHNOLOGIES AND THE HUMAN ELEMENT USING WORK DOMAIN ANALYSIS.

Ms. Claire Baker
School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Melbourne, VICTORIA, Australia
claireu.baker@gmail.com

Dr. Neelam Naikar
Defence Science and Technology Organisation (DSTO), Melbourne, VICTORIA, Australia
neelam.naikar@dsto.defence.gov.au

Prof. Mark Neerincx
TNO Defence, Security Safety, Soesterberg/ Delft University of Technology, Delft, The Netherlands
mark.neerincx@tno.nl

ABSTRACT

The realisation of sustainable space exploration and utilisation requires not only the development of novel concepts and technologies, but also their successful integration. Hardware, software, and the human element must be integrated effectively to make the dream for which these technologies were created a reality. Work Domain Analysis (WDA), the first phase of Cognitive Work Analysis, is becoming widely used for the holistic analysis and design of complex sociotechnical systems. However, the majority of these applications are for extant systems, or systems with a similar extant predecessor. This paper presents a brief introduction to WDA and a discussion of its application to the Mission Execution Crew Assistant (MECA). This application was performed to determine whether WDA is useful as a design tool for technologies without extant predecessors or operational experience, such as MECA, and also to evaluate a methodological approach to WDA developed in Australia. While improvements are suggested for the methodological approach, it was found to be an excellent source of guidance in the application of WDA. Outcomes of the application of WDA to the MECA system were found to be constructive for the MECA project team, indicating that WDA holds promise for application to first-of-a-kind systems in the space industry.

ENGINEERING THE FUTURE

To achieve sustainable space exploration and utilisation, the global space industry must continue to develop the required technologies within the next decade. The key to developing these technologies within a bounded timeframe will be the continued refinement of blue sky thinking to realistic achievement.

Just as important as the resulting technologies are the techniques and supporting technologies that underlie their development. Particular enablers are those techniques or technologies that facilitate the coming together of solutions from different disciplines to achieve a focussed overall solution.

The sustainable robotic and/or human occupation of space requires the successful integration of hardware, software, and the human element. In this paper, Cognitive Work Analysis (CWA) is proposed as a possible technique for the effective interdisciplinary development of space systems.

In the past, CWA has been applied successfully to the development of Earth-bound complex sociotechnical systems in which high levels of autonomy are often required of the human element. For example, CWA has been applied in the medical [1], maritime [2], [3], and defence industries [4].

This paper introduces CWA and discusses the application of a methodological approach for part of this technique within the space industry.

COGNITIVE WORK ANALYSIS

CWA is an approach for the analysis, design, and evaluation of complex sociotechnical systems.

Complex Sociotechnical Systems

Complex sociotechnical systems may be recognised by the following characteristics [5]:

- Many constituent parts and variables in large problem spaces;
- Social requirements, a need for large numbers of people to work together;
- Co-workers from diverse cultural backgrounds resulting in heterogeneous perspectives;
- Wide geographic spread resulting in a distributed system;
- A dynamic system, with the possibility that some parts of the system require long periods of time to fully react to changes in other parts;
- Mistakes made by workers may cause severe environmental, public safety, or economic consequences, i.e. the system is hazardous;
- Coupling – many links between constituent parts of the system;
- High levels of automation, with workers often only interfering directly when unanticipated events occur;
- Data supplied to workers can be inaccurate or ambiguous, causing uncertainty;
- Data required by workers is often not measurable via the use of human sensory capabilities, and mediated interaction (in the form of a computer interface, for example), is required to indicate system state/variables to the worker;
- Workers are often required to deal with disturbances, such as unanticipated events, in a manner that produces minimal effect on the system's operation or outcomes.

If we consider space exploration systems at the macro level, it becomes clear that these characteristics apply, in various combinations, to lunar, planetary or spacecraft-bound missions; both manned and robotic.

Phases of Cognitive Work Analysis

CWA involves five phases of analysis which, in combination, provide a thorough representation of the system and the work performed within it. The five phases, each of which has a different outcome, may be used individually or in combination to meet particular analysis requirements. The phases are as follows (the titles for each phase shown below are as given in [5]):

Work Domain Analysis identifies constraints (physical and purposive) imposed on the workers by the system.

Control Task Analysis identifies categories of events within the work domain, and the requirements associated with these events.

Strategies Analysis identifies methods for achieving events, and requirements related to these events.

Social Organisation and Cooperation Analysis identifies how work can be distributed between workers, and how workers can be organised within the system.

Worker Competencies Analysis identifies cognitive skills, rules and knowledge required to carry out the activities identified in the previous phases.

CWA and Systems Engineering

While CWA is most effective when used in conjunction with other analytic techniques, it can nevertheless provide a holistic system representation when used alone. As a result, CWA may be integrated effectively with many (if not all) areas of systems engineering, recognised internationally as the standard for system development, through life support, and retirement.

In an approach similar to systems engineering, CWA focuses not on individual system components, but on the system and its environment as a whole. This allows consideration of the constraints and affordances of the system at any time in the system lifecycle.

In addition to allowing individual problems to be solved, this holistic approach results in a system model that is comprehensible to individuals involved with the system, regardless of their backgrounds or levels of technical understanding.

THE NEED FOR AN EVENT-INDEPENDENT APPROACH

As noted above, CWA is most effective when used in combination with other system and work analysis techniques, such as task analysis (see, for example, [6]). However, WDA, the first phase of CWA, provides one important benefit over other analysis techniques in that it offers a formative, event-independent analysis.

Normative Approaches

Task analysis is currently the most commonly used method for assessing work in complex systems. The different approaches to task analysis aim to identify and/or assess the tasks required by workers [6]. These *normative* approaches describe what workers *should* do to achieve system goals [5].

Task analysis is effective when dealing with routine functions, however this approach has been found lacking in the early stages of system design, and when dealing with unanticipated situations. In system design, it is difficult to identify or predict all states that a system will encounter in its lifecycle. The earlier in the lifecycle this is attempted, the more difficult it becomes. It is also particularly difficult to predict system states a priori in complex systems, with unanticipated situations. Without defining system states, it is difficult to define how workers *should* act.

Through the study of worker behaviour. it has also become apparent that workers do not always follow prescribed actions or tasks. In addition, following predefined tasks is not always the best option, given the problem solving capacity of humans.

While normative approaches are effective when dealing with routine functions, they are limited when applied to complex sociotechnical systems, as they are closely linked to routine functions and do not take full advantage of the problem solving capabilities of humans.

Descriptive Approaches

Descriptive approaches, less commonly adopted in engineering fields, are used to identify work and system elements by describing how workers actually behave within the system. For the use of these methods, there is an obvious requirement for the system in question to already exist or have an existing analogue.

In a context such as space exploration in which systems are constantly changing and in which first-of-a-kind systems (for which we have no firsthand experience of the operating environment) are not uncommon, these methods are inefficient. Re-evaluation would be required each time a system modification occurs.

Formative Approaches

For complex sociotechnical systems, there exists a need to represent systems in a manner other than by describing how work is performed or prescribing certain tasks based on specific system states.

WDA aims to meet this requirement by representing the system in terms of environmental constraints. By describing a system in terms of its boundaries, analyses may be event-independent, rather than reliant on particular inputs or stimuli.

WORK DOMAIN ANALYSIS

As mentioned above, WDA, the first phase of CWA, identifies the environmental constraints imposed on the system. Constraints are either causal, determined by the laws of nature, or intentional, based on the laws, standards, and/or ethics of people involved with the system and its environment.

For example, an aircraft's operating environment imposes the causal constraint of the laws of aerodynamics and intentional constraints related to Federal Aviation Regulations.

The Abstraction and Decomposition Hierarchies

The system representation developed through WDA is known as the Abstraction-Decomposition Space (ADS) [5]. The ADS represents constraints and affordances of the system's operating environment in two hierarchies, the *Abstraction* and *Decomposition Hierarchies*.

The Abstraction Hierarchy represents *means-ends relationships* within the system environment. Elements at one level are the means to achieving elements at the next highest level, and the ends achieved by elements below (see Figure 1, top).

Two types of means-ends relationships exist: structural means-ends and action means-ends relationships. Structural means-ends relationships pertain to the physical and purposive form of the system, while action means-ends relationships pertain to actions required by the system. To maintain the event-independent nature of the analysis, the use of only structural means-ends relationships is recommended [5]. This avoids a systems representation which is limited by relationships which only describe means of achieving actions within the system.

The Decomposition Hierarchy represents *part-whole relationships*, with elements at one level being parts of elements represented at the level above, and composed of elements represented at the level below (see Figure 1, bottom).

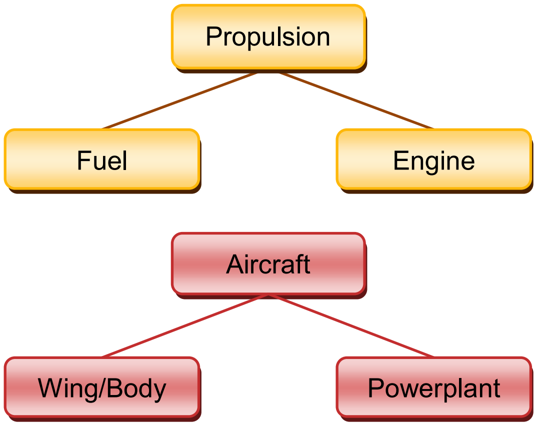


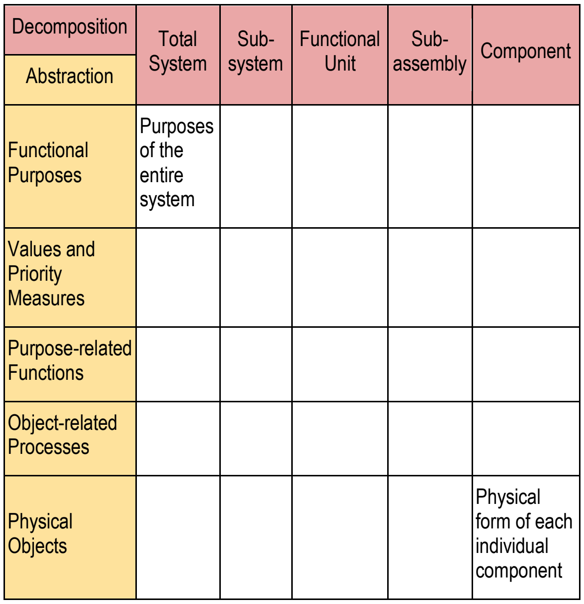
Figure 1: Examples of means-ends (top) and part-whole relationships.

The number of levels of abstraction and decomposition are not set, and are determined as part of the analysis. Representative names for the levels of decomposition and abstraction are given in Figure 2, however, these names are often tailored to suit the system under investigation.

<u>The Abstraction-Decomposition Space</u>

Once system information has been gathered and represented in the Abstraction and Decomposition Hierarchies, these hierarchies are combined to form the ADS. The Abstraction Hierarchy is on the vertical axis and the Decomposition Hierarchy is on the horizontal axis.

The ADS, often represented in table format as seen in Figure 2, is a collection of system representations. Each cell represents the same system, but at a different level of abstraction and detail to the surrounding cells. For example, the cell at the top left of the ADS represents the functional purposes of the system in its entirety. The cell at the bottom right of the ADS represents the physical description of each of the lowest level components of the system.



Decomposition Abstraction	Total System	Sub-system	Functional Unit	Sub-assembly	Component
Functional Purposes	Purposes of the entire system				
Values and Priority Measures					
Purpose-related Functions					
Object-related Processes					
Physical Objects					Physical form of each individual component

Figure 2: The Abstraction-Decomposition Space

The majority of information in the ADS is usually found along the diagonal between the two cells just described. This is due to the relationship between the Abstraction and Decomposition Hierarchies. It has been shown that, in practice, the higher the level of abstraction a person is considering, the lower the level of “resolution” at which they will consider the system [7]. So a person considering a system at a low level of abstraction might consider component detail. On the other hand, a person considering the functional purposes of the system would consider the system as a whole.

WDA: A METHODOLOGICAL APPROACH

Although there is much theoretical information about WDA and CWA in general, and although many applications of WDA exist, prior to 2005 there was little information available about a methodology for performing WDA [8].

The successful application of WDA to many projects within the Australian Defence Science and Technology Organisation (DSTO) has prompted an increase in the demand for its use. As evidenced by the large increase in CWA/Cognitive Engineering publications over the last five years, this demand is paralleled within other organisations worldwide. However, with few scientists and engineers experienced in the use of WDA, a requirement existed for a coherent methodological approach for WDA to enable the use of WDA by those who were not involved in its development.

The DSTO Centre for Cognitive Work and Safety Analysis developed a methodological approach to WDA with the aims of "making WDA more accessible to researchers and practitioners who were not involved in the development of WDA or who cannot be apprenticed to experts in WDA; reducing the amount of time and effort it takes to perform WDA even for experts in the area; and facilitating the application of WDA to large-scale, industry projects" [7, p. 3].

MISSION EXECUTION CREW ASSISTANT

Within this project, the methodological approach described in the previous section was applied within the Mission Execution Crew Assistant (MECA) project. MECA is a European Space Agency funded project currently being undertaken by TNO Human Factors, Science & Technology BV, OK-Systems, and EADS-Astrium. The demand for the MECA system comes from the recognition of the level of autonomy that will be required of planetary exploration crew.

MECA, a ubiquitous computing system, is being designed to aid the autonomous operation of human-machine exploration crews on Mars surface missions. One major role of MECA will be to provide critical support in unexpected and potentially hazardous situations, which will undoubtedly arise during planetary missions [9].

THE PROJECT

As a first-of-a-kind complex sociotechnical system, MECA provided an opportunity for an application of WDA within the space industry. The application had three potential benefits:

- Evaluation of the MECA Requirements Baseline (RB);
- Evaluation of the methodological approach to WDA, both in general and in relation to first-of-a-kind systems; and
- Evaluation of the usefulness of WDA for first-of-a-kind systems for which there is limited experiential information.

Evaluation of the MECA Requirements Baseline

The MECA project team recognises that the successful exploration of the Mars surface environment will require Human-Machine Collaboration (HMC), that is, the effective integration of technology with human task execution. This premise indicates that complete evaluation of the system will only occur through the joint consideration of human and machine adaptive behaviour.

Using a Cognitive Engineering method [9], [10], the MECA team developed and refined the project Requirements Baseline (RB). This RB enabled the correct and focussed development of technology to meet system (operational and human factors) needs [11].

It was identified that as a part of this Cognitive Engineering method, WDA had the potential to assess the RB for completeness and accuracy. By defining the surface operating environment, WDA might assess whether the RB accurately defined a system that would effectively, efficiently, and safely achieve surface exploration within this environment. More specifically, the requirements could be analysed in relation to the ADS to ensure that they defined a system capable of Mars exploration within the constraints and affordances of the environment in which MECA will operate.

Evaluation of the Methodological Approach

Prior to this evaluation of the MECA RB, applications of WDA within the DSTO had only been performed by research scientists who are, or have access to assistance from, CWA experts. This application of WDA to the MECA RB provided two distinct opportunities for the evaluation of the DSTO methodological approach to WDA. First, it provided an opportunity for the evaluation of the approach by someone who was not involved in its development. Second, it provided an opportunity for the evaluation of the methodological approach by someone who is not an expert in CWA.

To enable the DSTO Centre for Cognitive Work and Safety Analysis to further develop the methodological approach, the evaluation of the approach aimed to determine the following [12]:

- Whether or not the methodological approach allows the analyst to create a valid system representation;
- Whether or not the methodological approach directs the analyst in a manner that allows them to use WDA to achieve their initial aims;
- Whether or not the methodological approach is comprehensible and easy to use; and
- Whether or not the methodological approach presents a practical approach to WDA.

Applicability to First-of-a-Kind Systems

One challenge that is particularly relevant to the space industry is the limited amount of first-hand experience in the operational environment, that is, in orbiting systems and lunar and planetary missions.

In any evaluation, the greater the amount of correct information used, the more valid the outcome. However if we are to focus on the MECA system operating within a manned planetary exploration mission, we are forced to work with information based on robotic research and Earth analogues: we have no firsthand experience of the environment from which to draw information for the analysis.

This application of WDA therefore provides another opportunity to test the robustness of WDA, and the WDA methodological approach, where primary information sources are scarce or non-existent.

METHODOLOGICAL APPROACH APPLICATION FOR MECA

The following section discusses the application of the methodological approach in order to evaluate the MECA requirements baseline. The process is broken down to each of the "steps" of the methodological approach (which are described in detail in [8]).

Step 1: Establish the purpose of the WDA

The purpose of the WDA was to evaluate the MECA RB including task level, functional, user interface, technical interface, operational, and technical requirements [9], and to suggest any new requirements arising from the analysis.

The RB would be evaluated by comparing it to a representation of the environment in which MECA would be required to function. That is, WDA would provide an ADS representing the constraints and affordances of the Mars surface environment including the natural environment, man-made objects, and regulatory components. Requirements within the baseline would then be assessed according to this ADS to ensure they defined a system which would operate effectively within the exploration environment.

Step 2: Identify Project Constraints

Project constraints related to time, budget, and available human resources. The project (an undergraduate thesis project) was limited to a maximum of three months and was unfunded. Only one analyst performed the application.

These constraints restricted the scope of the analysis and the number of documents utilised in the creation of the ADS. These constraints also imposed strict time limits on each step of the methodological approach.

Step 3: Determine the Boundaries of the WDA

This step involved defining the "focus system" or the particular aspects of the Mars surface environment to be included in the analysis. In this project, the focus system was defined as incorporating the following [12]:

- Communications and any hardware/software required for communications between the Mars outpost and Mission Command and Control (MCC), and any mission objectives or regulations specified by MCC;
- Rovers;
- Robots (teleoperated and autonomous) and other remotely operated devices;
- Facilities such as power generation, oxygen generation etc.;
- Launch/landing facilities;
- Astronaut hardware/software (ranging from habitats to extravehicular suits and related software); and
- The surface physical and atmospheric environment of the outpost and any area considered for exploration and reconnaissance.

These boundaries were further refined throughout the remaining steps of the analysis, as the analyst's knowledge of the domain increased.

Step 4: Identify the Nature of Constraints

This step of the approach deals with identifying whether constraints are predominantly causal or intentional. The Mars surface exploration environment exhibits both types of constraint, with a higher number of causal constraints.

Causal constraints stem from the highly technical nature of missions and the physical environment itself. Intentional constraints exist due to the explorative nature of the mission, the intentions of crew members, regulations surrounding the mission (for example interplanetary quarantine regulations), and public expectations.

Step 5: Identify Potential Sources of Information

As discussed earlier, sources of first-hand information for planetary exploration environments are limited. This is particularly true for manned missions. The sources identified included: technical papers, mission statements, and other documents related to planetary exploration; MECA project documents such as feasibility studies and requirements documents (other than the RB itself); and information from MECA experts.

Information for the various stages of CWA is often obtained using methods such as walk-throughs and talk-throughs, and interviews with subject matter experts[*]. Although it is not possible to "walk through" the surface exploration environment, and no-one has yet experienced the environment and become a system expert, using analogue environments such as the Mars Analogue Research Station would have been beneficial for this analysis. However, it was not possible to do so for this project.

Steps 6-9: Construct ADS, Three Iterations

Steps 6 to 9 of the methodological approach involve examining the available sources of information to iteratively develop the ADS for the focus system.

Initially, this process involved identifying work domain properties and grouping them into categories. For example, three work domain properties identified were "daily planning conferences", "private medical conferences", and "family conferences". These were all categorised as "conferences". Once the analyst had a greater understanding of the work domain, it was possible to begin identifying relationships between work domain properties to establish the Abstraction and Decomposition Hierarchies.

The methodological approach recommends the creation of a glossary during ADS development to aid in the consistent definition of terms in relation to the system. Throughout the iterative development of the Mars surface exploration ADS, this glossary proved a very useful tool, not only for ensuring consistent definition of terms, but also in ensuring that the ADS itself did not include excessive information about work domain properties.

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[*] For the purposes of this paper, people with extensive knowledge about the system and its operating environment, but no first-hand experience with either, are considered *subject matter experts*. People with first-hand experience of the system and its operating environment are considered *system experts*.

The Abstraction and Decomposition Hierarchies

As suggested in the methodological approach, “how” and “why” questions were asked when considering the information, to help determine the number of levels of abstraction for the system. For example, the question “How is Crew Health maintained?” led to the definition of “Health Management” as a means of achieving “Crew Health”. These questions led to an initial impression of how many levels of abstraction would exist within the system.

In the first iteration, it was found that the majority of literature represented functions with verbs, rather than nouns. As the verbs in general represented action within the system, rather than the physical or purposive form of the system, it was difficult to establish structural means-ends relationships. In the initial iterations of the ADS, verbs were used to represent functions. However, as the analyst’s knowledge of the system increased, it was possible to “translate” work domain properties so that they were represented with nouns. Careful analysis of the abstraction relationships between these work domain properties then ensured that only structural means-ends relationships were represented in the ADS.

While physical work domain properties were initially the easiest to identify within the available literature, establishing the part-whole relationships between work domain properties was more difficult. This was due to the fact that the physical systems to be used in surface exploration missions are under development. Hence while individual components may have been defined, how they will be used in conjunction with one another may not have been considered.

The range of sources from which information was obtained also caused difficulty with respect to defining both abstraction and decomposition relationships. The same work domain properties were often noted in many sources, but defined differently.

For example, “field exploration” in one document was defined as being composed of “reconnaissance” and “field work”. A second source also included “laboratory investigation” with collected samples as part of the definition. A third source indicated that “field exploration” would commence using information obtained through reconnaissance, indicating that “reconnaissance” was a means to achieve “field exploration”, and not a part of it. As the MECA contract is directed by ESA, where a relationship could not be established through the amalgamation of information from different sources, ESA information took precedence.

Six levels of abstraction were initially defined using “tailored” headings:

1. Mission Priorities (Where “mission” refers to the Mars surface mission in its entirety)
2. Values and Priority Measures
3. Priority-Related Functions
4. Mission-Related Functions
5. Physical Capability
6. Physical Objects

As further information was reviewed, it became apparent that work domain properties at the third level of abstraction were difficult to decompose. Furthermore, it was difficult to establish relationships between work domain properties at the third level of abstraction and work domain properties at the levels above and below. It became clear that this level of abstraction was in fact a representation of work domain properties at a greater level of detail than the work domain properties at the level below it. It was not a different and complete representation of the system, as each level of abstraction should be.

To establish the “correct” number of levels of abstraction, several work domain properties (for which large amounts of information were available) were summarised [12] by noting what they required, functions of the property, why they existed, and constraints surrounding them.

For example:

Work Domain Property: Field Exploration

Requires:

Maps; overhead photos; surface navigation system; tools/instruments; communications equipment; unpressurised rover; pressurised rover; trailer, wagon, and/or trolley; drill; teleoperated robots; safe havens; geophysical/meteorological stations; EVA suits; field camp; automated robots; telerobot control station; communications system.

Functions:

Traverse; observe; data recording; communication; sample collection; sample curation; station set-up; navigation; documents; planning; experiments.

Why:

To gain an understanding of a particular area of Mars including: resources; history (geophysical, etc.); possible signs of extant or extinct life. Completing Field Exploration would be considered one part of mission success. Also: Productivity (affects crew health, public/political attention, acceptance and support).

Constraints:

EVA suit endurance; rover range; crew constraints; local sunset.

Summarising information in this way simplified the process of transferring information to the Abstraction Hierarchy. Using this method, five levels of abstraction became clear from the available information, confirming that one of the six earlier levels was not a different and complete system representation.

Combination of the Abstraction and Decomposition Hierarchies then led to a "sketch" of the ADS. The methodological approach recommends populating the cells on the diagonal of the ADS initially, as "workers tend to adopt purposive models when working at coarse levels of resolution and physical models when working at fine-grained levels of resolution" [7, p. 42].

This sketch was then developed into a complete ADS through the continued addition and refinement of work domain properties and the connection of abstraction and decomposition relationships.

Step 9: Validate the ADS

Validation of the ADS is necessary to ensure it can accommodate actors' reasoning in a variety of situations and thus accurately represents the system being modelled [8].

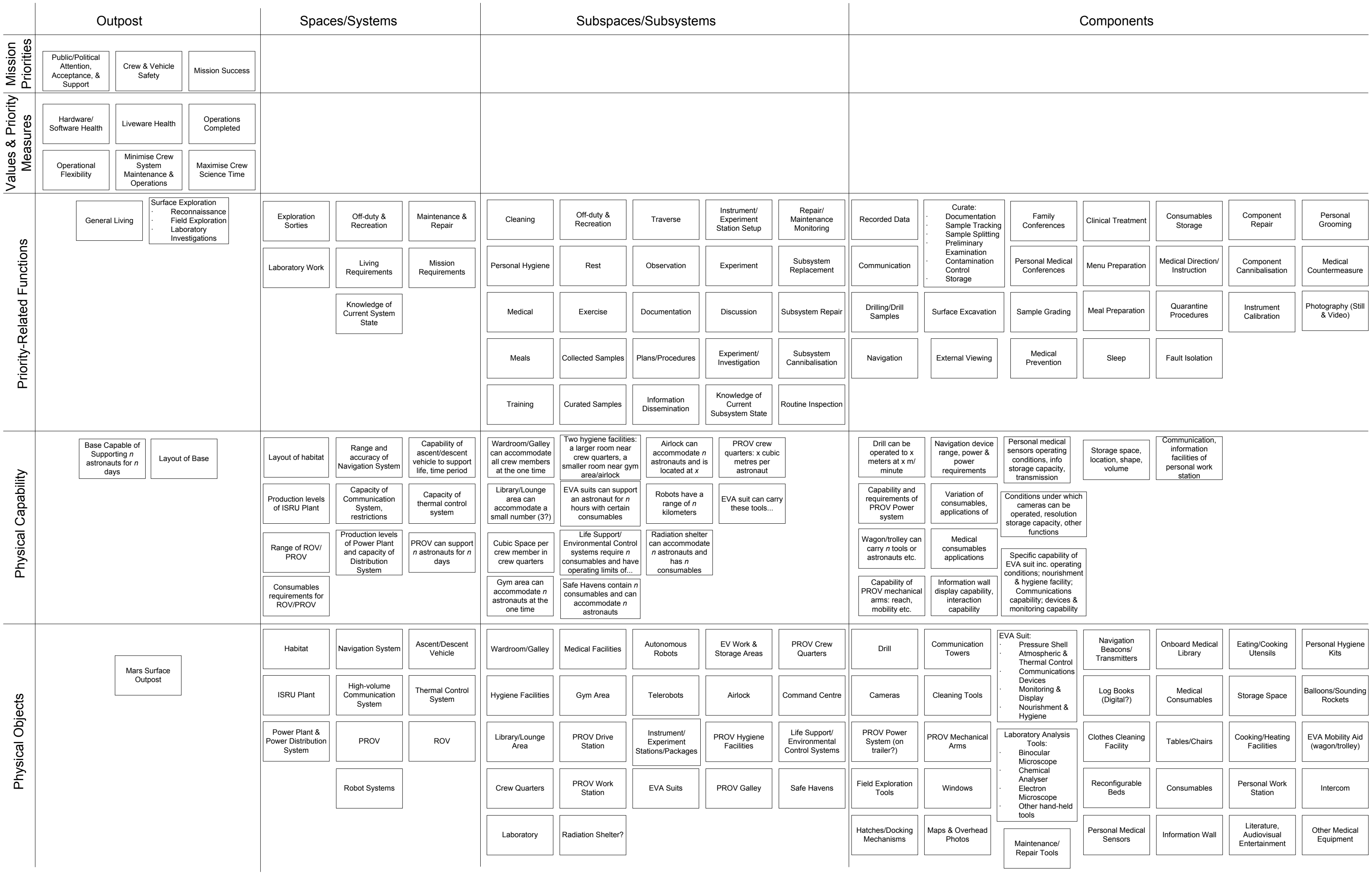
As we have not yet experienced the Mars surface environment and hence system experts do not exist, other subject matter experts were consulted for the validation in this application. A set of questions, based on suggestions given in the methodological approach for formation of the ADS, were given to members of the MECA team. As MECA was, at that time, still in an early phase of development, the questions focussed on the first three levels of abstraction, rather than on lower, more physical levels.

The answers to these questions successfully validated the ADS. The only changes required were additions to and refinement of terms in the glossary that was developed in parallel with the ADS.

The final Mars surface exploration ADS is shown in Figure 3.

EVALUATING THE MECA REQUIREMENTS BASELINE

The evaluation of the RB using the ADS was performed in two stages. Firstly, each work domain property within the first three levels of the ADS (i.e., *Mission Priorities*, *Values and Priority Measures,* and *Priority-Related Functions*) was compared to the RB. This comparison aimed to ensure that all work domain properties were taken into consideration by one or more requirements in the RB. If so, the system defined by the RB would function effectively within the defined Mars surface exploration environment.



	Outpost	Spaces/Systems	Subspaces/Subsystems	Components
Mission Priorities	Public/Political Attention, Acceptance, & Support Crew & Vehicle Safety Mission Success			
Values & Priority Measures	Hardware/ Software Health Liveware Health Operations Completed Operational Flexibility Minimise Crew System Maintenance & Operations Maximise Crew Science Time			
Priority-Related Functions	General Living Surface Exploration · Reconnaissance · Field Exploration · Laboratory Investigations	Exploration Sorties Off-duty & Recreation Maintenance & Repair Laboratory Work Living Requirements Mission Requirements Knowledge of Current System State	Cleaning Off-duty & Recreation Traverse Instrument/ Experiment Station Setup Repair/ Maintenance Monitoring Personal Hygiene Rest Observation Experiment Subsystem Replacement Medical Exercise Documentation Discussion Subsystem Repair Meals Collected Samples Plans/Procedures Experiment/ Investigation Subsystem Cannibalisation Training Curated Samples Information Dissemination Knowledge of Current Subsystem State Routine Inspection	Recorded Data Curate: · Documentation · Sample Tracking · Sample Splitting · Preliminary Examination · Contamination Control · Storage Family Conferences Clinical Treatment Consumables Storage Component Repair Personal Grooming Communication Personal Medical Conferences Menu Preparation Medical Direction/ Instruction Component Cannibalisation Medical Countermeasure Drilling/Drill Samples Surface Excavation Sample Grading Meal Preparation Quarantine Procedures Instrument Calibration Photography (Still & Video) Navigation External Viewing Medical Prevention Sleep Fault Isolation
Physical Capability	Base Capable of Supporting *n* astronauts for *n* days Layout of Base	Layout of habitat Range and accuracy of Navigation System Capability of ascent/descent vehicle to support life, time period Production levels of ISRU Plant Capacity of Communication System, restrictions Capacity of thermal control system Range of ROV/ PROV Production levels of Power Plant and capacity of Distribution System PROV can support *n* astronauts for *n* days Consumables requirements for ROV/PROV	Wardroom/Galley can accommodate all crew members at the one time Two hygiene facilities: a larger room near crew quarters, a smaller room near gym area/airlock Airlock can accommodate *n* astronauts and is located at *x* PROV crew quarters: x cubic metres per astronaut Library/Lounge area can accommodate a small number (3?) EVA suits can support an astronaut for *n* hours with certain consumables Robots have a range of *n* kilometers EVA suit can carry these tools... Cubic Space per crew member in crew quarters Life Support/ Environmental Control systems require *n* consumables and have operating limits of... Radiation shelter can accommodate *n* astronauts and has *n* consumables Gym area can accommodate *n* astronauts at the one time Safe Havens contain *n* consumables and can accommodate *n* astronauts	Drill can be operated to x meters at x m/ minute Navigation device range, power & power requirements Personal medical sensors operating conditions, info storage capacity, transmission Storage space, location, shape, volume Communication, information facilities of personal work station Capability and requirements of PROV Power system Variation of consumables, applications of Conditions under which cameras can be operated, resolution storage capacity, other functions Wagon/trolley can carry *n* tools or astronauts etc. Medical consumables applications Specific capability of EVA suit inc. operating conditions; nourishment & hygiene facility; Communications capability; devices & monitoring capability Capability of PROV mechanical arms: reach, mobility etc. Information wall display capability, interaction capability
Physical Objects	Mars Surface Outpost	Habitat Navigation System Ascent/Descent Vehicle ISRU Plant High-volume Communication System Thermal Control System Power Plant & Power Distribution System PROV ROV Robot Systems	Wardroom/Galley Medical Facilities Autonomous Robots EV Work & Storage Areas PROV Crew Quarters Hygiene Facilities Gym Area Telerobots Airlock Command Centre Library/Lounge Area PROV Drive Station Instrument/ Experiment Stations/Packages PROV Hygiene Facilities Life Support/ Environmental Control Systems Crew Quarters PROV Work Station EVA Suits PROV Galley Safe Havens Laboratory Radiation Shelter?	Drill Communication Towers EVA Suit: · Pressure Shell · Atmospheric & Thermal Control · Communications Devices · Monitoring & Display · Nourishment & Hygiene Navigation Beacons/ Transmitters Onboard Medical Library Eating/Cooking Utensils Personal Hygiene Kits Cameras Cleaning Tools Log Books (Digital?) Medical Consumables Storage Space Balloons/Sounding Rockets PROV Power System (on trailer?) PROV Mechanical Arms Laboratory Analysis Tools: · Binocular Microscope · Chemical Analyser · Electron Microscope · Other hand-held tools Clothes Cleaning Facility Tables/Chairs Cooking/Heating Facilities EVA Mobility Aid (wagon/trolley) Field Exploration Tools Windows Reconfigurable Beds Consumables Personal Work Station Intercom Hatches/Docking Mechanisms Maps & Overhead Photos Maintenance/ Repair Tools Personal Medical Sensors Information Wall Literature, Audiovisual Entertainment Other Medical Equipment

Figure 3: The Completed ADS

An example of this evaluation is as follows. A work domain property from the *Values and Priority Measures* level of abstraction for the defined environment is “Minimise Crew System and Maintenance Operations”. This value is taken into consideration in two entries from the MECA RB, namely:

- “MECA shall have the capability to execute procedures autonomously when delegated by the crew”; and
- “MECA shall provide the possibility to release the crew from continuously monitoring and controlling the vehicles and equipment that operate autonomously”.

Secondly, if a work domain property from the first three levels of abstraction was not evidenced in the requirements, then the abstraction relationships within the ADS were used to determine the extent of the impact of the omission.

This final evaluation became difficult due to language differences between the RB and the ADS and related glossary. This difficulty might have been reduced had the RB been considered in the early stages of the analysis. This option was considered, but rejected because the ADS was being used to validate the RB. Any bias introduced into the ADS due to consideration of the RB may have influenced the final outcome.

Final Outcome of the RB Evaluation Process

The conclusion of the evaluation process was that, according to the ADS, the MECA development had indeed considered all aspects of the Mars surface mission. While all work domain properties were evidenced in the RB, some work domain properties had a larger number of supporting requirements than others.

In order to obtain a more complete requirements solution for the mission, the analyst suggested that more consideration of requirements in the area of general living during the mission was required. “General Living,” according to the ADS glossary, included those functions required to maintain crew health and the operational mode of the outpost in order to complete mission objectives and maintain public and political support and acceptance.

WDA POTENTIAL IMPROVEMENT AREAS AND BENEFITS

Throughout the analysis of the MECA operating environment and RB, several areas for growth of the WDA methodological approach and WDA in general were identified, along with several particular advantages of the approach.

Use of the Methodological Approach for WDA

The methodological approach provided a level of guidance for performing WDA not found elsewhere in CWA literature. Whilst the “steps” of the analysis provided comprehensive instructions and “lessons learned” from the authors’ applications, it became apparent during the MECA operating environment analysis that the majority of the steps of the approach were iterative.

In light of this finding, it is recommended that the CWA methodology be altered to present the approach in phases, with overlapping sections where required, and to note that as the analysis progresses, it may be necessary to review (parts of) earlier phases.

Application to First-of-a-Kind Systems

As with all types of analysis, any shortcomings in the information used for performing a WDA will affect the quality of the results produced from it. This WDA was performed within a short timeframe and tight resource constraints. Nevertheless, it was capable of providing a useful system representation, as assessed by members of the MECA project team.

This is a promising beginning for the further use of WDA in the space industry, where first-of-a-kind systems remain commonplace. It is surmised that additional sources of information (in particular, from analogue systems, which were not used in this analysis, and from subject matter experts) and an increase in resources for the analysis would greatly enhance the results and benefits of such analyses.

Critical Paths

The ADS achieves a common engineering goal: it presents a realistic and accurate system representation that is independent of any specific events. In particular, the Abstraction Hierarchy displays relationships within this system representation, illustrating workers' reasoning processes and critical resource paths at lower levels of abstraction. For example, the removal of a physical component at the lowest level of abstraction may propagate through the ADS (using abstraction relationships) to impact the achievement of the highest-level aims of the system.

A development of WDA which may allow for more widespread use of the ADS would be a means to represent other types of critical paths "at a glance". One particular benefit of doing this in a WDA is that the ADS is already in language comprehensible by project team members from different disciplines.

Many of these "paths" would be event-dependent, for example time- or finance-critical paths, and as such could not be considered during the development of the ADS. However, if these paths could be represented in the ADS, the ADS would have even greater benefits for a larger number of team members throughout the project lifecycle.

Volume of Information for Analysis

The amount of information required for the construction of the ADS, both in terms of the number of resources used and the number of work domain properties identified, can be at times overwhelming for the analyst. The usefulness of Microsoft Visio for the construction of the Abstraction Hierarchy in this and another analyses performed for evaluation of the methodological approach (Baker, 2006), indicated that a customised software solution for the display and organisation of information would be preferable. A customised solution would allow certain sections of information to be linked to others, and to be viewed in isolation or holistically. In addition, configuration management would be improved.

A software solution tailored to WDA (or ultimately to all phases of CWA) would be a stepping stone to the widespread use of WDA. However, as with any software, there would be a risk that the improved usability facilitated by the software package would increase incorrect use of the technique.

Language and Terminology

Whilst the lower levels of abstraction and decomposition were relatively simple to compose, difficulties arose in the "translation" of information into the higher levels of abstraction.

In general, this was due to the nature of the ADS (structurally oriented), as compared to the nature of the information being used, and also the background of the analyst (an engineer, with no prior experience in CWA). The majority of available information uses verbs rather than nouns to describe the functions of the system, leading to difficulties in translation. For example, it was difficult to convert the activities "walking around", "observing", "performing experiments", and "collecting samples", into nouns (without connotation of action) which effectively describe the elements of "field exploration".

As an engineer, it was also difficult for the analyst to review information with the identification of work domain properties in mind. In the initial stages of the analysis, information often had to be reviewed two or three times, as the analyst had instinctively focussed on engineering aspects and had not recognised work domain properties.

Vicente [4, p. 163] comments that "It takes a great deal of practice – and perhaps cognitive style – to think fluently in terms of means-ends relations". More widespread use of WDA, and several more instances of its use by those without prior experience in CWA, will be required before the suitability of this method for non-expert use can be determined.

The analyst also required practice in the identification of relationships between causal and intentional work domain properties. The requirement for practice was partially due to the separation of causal and intentional work domain properties in the literature examined during the analysis. These two different types of property were rarely found in the same documents (or parts of documents). It appears that domain knowledge and CWA experience are, at this stage, the only aids to identifying these relationships.

PROJECT BENEFITS AND FUTURE PROSPECTS

Specific Benefits of the WDA for the MECA Project

The application of WDA for the MECA project was an effective approach for obtaining a complementary, but alternative, means for evaluation of the RB. The application of WDA by an analyst not involved in the MECA team itself provided a means to achieve the evaluation without creating a drain on the project resources - a particular advantage considering the trial nature of the application, with no guaranteed project-applicable results.

Glossary

The glossary created during the analysis was an extremely useful tool for ensuring consistency, not only in the definition of work domain properties, but in the definition of information in general. It also proved a useful tool for managing information without confusion, particularly through the use of hyperlinks for fast access of related information.

One surprise following the evaluation was the usefulness of this glossary for the MECA team. The glossary became a method for ensuring a common vocabulary throughout the project. Similar to the ADS itself, the glossary has the potential to be used as a dynamic information store, throughout the system lifecycle. It is also simple to understand, update, and manage.

The MECA team identified the opportunity to use the glossary further in the project, to aid in the creation of an ontology for MECA. Such an ontology is required to achieve a high level of autonomy, for which the MECA software must have an understanding of *both* high level mission objects (such as goals, re-sources, actors, tasks, procedures, plans and schedules) *and* lower-level system information (such as vehicles, payloads, instruments, sensors, actuators, processors, telemetry, test results, and fault diagnoses). Furthermore, the ontology should include human issues such as cognitive task load, emotion, fitness and social involvement, to accommodate human-machine partnership and sharing of information by both human and machine actors. For the first MECA demonstrators, the MECA team used a distributed Resource Description Framework (RDF) knowledge base, containing heterogeneous data described by various Ontology Web Language (OWL) ontologies (OWL and RDF are part of the W3C building block standards for the Semantic Web).

The common semantic worldview provided by the RDF data made it possible and even easy for the software to be aware of and reason about connections between concepts and data that are not normally considered interoperable. It was also instrumental in implementing parts of MECA as semantic web services, facilitating the sharing of knowledge among heterogeneous agents [13].

Further iterations and refinements

In addition to the WDA-based validation and standard (“formal”) requirements reviews, the MECA consortium tested and refined the RB via storyboarding and human-in-the-loop evaluations of a simulation-based prototype in a virtual environment [14]. The evaluation confirmed the predicted results. Issues for improvement and further research were identified and prioritized (e.g., acceptance of mental load and emotion sensing). Projects are being started for MECA implementation and evaluation for a long duration isolation study (MARS 500), onboard the International Space Station (ISS), and at a terrestrial Moon or Mars analogue environment.

CONCLUSION AND RECOMMENDATIONS

The success of this application of WDA, in spite of time and resource limitations, is an indication of the potential suitability of WDA in engineering first-of-a-kind and replacement systems for space exploration and utilisation. Additional research should be designed to further test the benefits of WDA for first-of-a-kind systems.

Validation of the potential benefits of integration with systems engineering would also be constructive. Development of WDA (and CWA in general) requires an increase in applications by non-experts, supported by knowledge sharing throughout the industry.

Development should include the creation of software packages for use with WDA, which should support WDA through functionality such as the display of particular types of relationships and work domain properties, the display of critical paths, and the capacity for linking to glossary terms.

Time will be required to develop the methodology to a level where it provides meaningful results efficiently, and with minimal resources, when used by non-experts. However, the potential for considerable benefit exists, not only in the direct output of the tool itself, but also in indirect outputs such as the glossary.

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REFERENCES

[1] J.R. Hajdukiewicz, D.J. Doyle, P. Milgram, K.J. Vicente, and C.M. Burns, “A Work Domain Analysis of Patient Monitoring in the Operating Room” in *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting,* Santa Monica, 1998, p. 1038-1042.

[2] C.M. Burns, D.J. Bryant, and B.A. Chalmers, “Boundary, Purpose, and Values in Work Domain Model: Models of Naval Command and Control”, *IEEE Transactions on Systems, Man and Cybernetics Part A*, p. 603-616, 2005.

[3] C.M. Burns, D.J. Bryant, and B.A. Chalmers, “A Work Domain Model to Support Shipboard Command and Control.” *IEEE International Conference on Systems, Man, and Cybernetics.* Nashville, 2000, p. 2228-2233.

[4] N. Naikar, and P.M. Sanderson, “Evaluating Design Proposals for Complex Systems with Work Domain Analysis”, *Human Factors*, vol. 43, no. 4, p. 529-543, 2001.

[5] K. Vicente, *Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer Based Work.* London: Lawrence Erlbaum Associates, 1999.

[6] B. Kirwan, and L. Ainsworth, *A Guide to Task Analysis*, London: Taylor & Francis Ltd, 1992.

[7] K. Vicente, K. Christoffersen, & A. Pereklita, “Supporting operator problem solving through ecological interface design”, *IEEE Transactions of Systems, Man, & Cybernetics*, vol. 25, p. 529-545, 1995.

[8] N. Naikar, R. Hopcroft, and A. Moylan, *Work Domain Analysis: Theoretical Concepts and Methodology*, Australian Defence Science and Technology Organisation, Melbourne, Australia, 2005.

[9] M. Neerincx, J. Lindenberg, N.J.J.M. Smets, T. Grant,. A. Bos, U.A. Olmedo Soler, U. Brauer, and M. Wolff, “Cognitive Engineering for Long Duration Missions: Human-machine Cooperation on the Moon and Mars” in *SMC-IT 2006: 2nd IEEE International Conference on Space Mission Challenges for Information Technology,* p. 40-46. Los Alamitos, California: IEEE Conference Publising Services., 2006.

[10] Neerincx, M.A. & Lindenberg, J. (2008). Situated cognitive engineering for complex task environments. In: Schraagen, J.M.C., Militello, L., Ormerod, T., & Lipshitz, R. (Eds). *Naturalistic Decision Making and Macrocognition* (p. 373-390). Aldershot, UK: Ashgate Publishing Limited.

[11] Neerincx, M.A. Bos, A., Olmedo-Soler, A. Brauer, U. Breebaart, L., Smets, N., Lindenberg, J., Grant, T., Wolff, M. (2008). The Mission Execution Crew Assistant: Improving Human-Machine Team Resilience for Long Duration Missions. *Proceedings of the 59th International Astronautical Congress (IAC2008)*, Glasgow.

[12] C.U. Baker, “Evaluation and Refinement of a Methodological Approach for Work Domain Analysis” B.Eng Thesis, RMIT University, Melbourne, Australia, 2006.

[13] Breebaart, L., Bos, A., Grant, T., Olmedo-Soler, A., Neerincx, M.A., Smets, N., Brauer, U. and Wolff, M. (2008). The MECA project: Using an OWL/RDF knowledge base to ensure data portability for human space mission operations *10th NASA-ESA Workshop on Product Data Exchange*, 26-28 March 2008. Noordwijk, The Netherlands.

[14] Smets, N.J.J.M., Abbing, M.S., Neerincx, M.A., Lindenberg, J, and van Oostendorp, H. (2008). Game-based evaluation of personalized support for astronauts in long duration missions. *Proceedings of the 59th International Astronautical Congress (IAC2008)*, Glasgow.