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ExPeRT Technology Management Tool in the framework of the European ISRU Technologies

Tesi di Laurea Magistrale in
Space Engineering - Ingegneria Spaziale

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Abstract

Within the Space domain in Europe the European Space Agency plays a central part: with the goal of bringing mankind to Mars, the Human & Robotic Exploration Directorate is operating in the Exploration panorama. The European Exploration Envelope Programme (E3P) was funded at this purpose, and as part of it, the Exploration, Preparation, Research and Technologies (ExPeRT) team was entrusted of the management of its technology process, in particular the definition, planning, implementation, development, monitoring, and coordination of technologies for future exploration missions to low Earth orbit (LEO), Moon, and Mars.

The technology branch at ESA is composed of several programmes which collaborate to enable new technologies and capabilities. The technologies under the ExPeRT domain are relevant to Exploration, to enable the key mission identified in the context of the E3P. The end-to-end exploration technology process, from the formulation of a technology need until the successful implementation follows a tortuous path, involving different stakeholders and information exchange. The thesis is investigating the possibility of supporting the technology life-cycle by means of a technology management tool using a system model able to represent the existing object-process flow for technology development in ExPeRT. This model, in the form of a software tool, requires interfacing with various input and output data formats, as well as with other existing tools in a pre-defined architecture environment.

The Technology Management Tool (TMT) is currently used in ExPeRT to manage technology activities for future exploration missions. The In Situ Resource Utilization (ISRU) domain is taken as user case to demonstrate TMT capabilities, producing the update of the ISRU European Technology Roadmaps previously formulated in 2020.

Keywords: ESA, Low TRL Technology, Space Exploration, Database, Management, ExPeRT Team, ISRU

Abstract in lingua italiana

Nel settore spaziale europeo, l'Agenzia Spaziale Europea svolge un ruolo centrale: con l'obiettivo di portare l'uomo su Marte, il Direttorato di Esplorazione Umana e Robotica opera nel panorama dell'esplorazione. A questo scopo è stato finanziato il Programma European Exploration Envelope (E3P), nell'ambito del quale il team Exploration, Preparation, Research and Technologies (ExPeRT) è stato incaricato di gestirne il processo tecnologico, in particolare la definizione, la pianificazione, l'implementazione, lo sviluppo, il monitoraggio e il coordinamento delle tecnologie per le future missioni di esplorazione dell'orbita terrestre bassa (LEO), della Luna e di Marte.

Il ramo tecnologico dell'ESA è composto da diversi programmi che collaborano per abilitare nuove tecnologie e capacità. Le tecnologie del settore ExPeRT sono rilevanti per l'esplorazione, per consentire le missioni chiave identificate nel contesto dell'E3P. Il processo tecnologico end-to-end di esplorazione, dalla formulazione di un'esigenza tecnologica fino all'implementazione di successo, segue un percorso tortuoso, coinvolgendo diversi stakeholder e interscambio di informazioni. La tesi studia la possibilità di supportare il ciclo di vita delle tecnologie attraverso uno strumento di gestione tecnologica che utilizzi un modello di sistema in grado di rappresentare il flusso di oggetti-processi esistente per lo sviluppo della tecnologia in ExPeRT. Questo modello, sotto forma di strumento software, richiede l'interfacciamento con vari formati di dati in ingresso e in uscita, nonché con altri strumenti esistenti in un ambiente ad architettura predefinita.

Technology Management Tool (TMT) è attualmente utilizzato in ExPeRT per gestire le attività tecnologiche per le future missioni di esplorazione. L'ambito di In Situ Resource Utilization (ISRU) è stato preso come user case per dimostrare le capacità di TMT, producendo l'aggiornamento delle Roadmap tecnologiche europee sull'ISRU precedentemente formulate nel 2020.

Parole chiave: ESA, Tecnologia a basso TRL, Esplorazione Spaziale, Database, Management, ExPeRT Team, ISRU

Acknowledgements

Poichè queste parole rappresentano le ultime da me trascritte prima di concludere il mio percorso di studi sembrerebbe opportuno sceglierle con cura. Al contrario, per una volta mi voglio prendere la libertà di includere in questo ultimo capitoletto trascritto della mia vita universitaria tutto quello che mi passa per la testa, senza filtri. Finalmente.

E' quasi spaventoso voltarsi indietro e pensare a quello che è successo negli ultimi 2 anni e mezzo. Mi ricordo come se fosse ieri quando sono arrivato in Via Armellini con tutte le valigie, mi ricordo il casino di riordinare la stanza, mi ricordo quando volevo spostare la scrivania per studiare sotto la finestra, per vedere fuori. Mi ricordo come se fosse ieri quella mattina di Settembre del 2020 quando mi sono ritrovato in aula, seduto, ad assistere alla prima lezione, e non conoscevo davvero nessuno. Mi ricordo anche quando, dopo 2 anni, il 12 Luglio del 2022 ho dovuto svuotare la stanza in cui ho vissuto per 2 anni. Mi ricordo quando con 4 valigie contenenti praticamente tutto quello che posseggo sono arrivato alle 09.15 alla stazione di Leiden centrale il 12 Agosto 2022, dopo aver dormito una una notte in aeroporto a Milano, di nuovo solo. Mi ricordo il primo giorno di tirocinio, quando ho preso l'autobus per andare ad ESTEC. Mi ricordo anche quando, dopo 7 mesi, il primo Febbraio di questo 2023, sono decollato dall'Olanda per tornare nuovamente a casa.

C'è una dannata domanda che continuo a farmi da sempre. Che cosa è esattamente casa quando fai una valigia dopo l'altra contenente tutto quello che "hai"? Da quando ho iniziato il mio percorso di studi ho sempre detto di possedere 2 vite: quella a CASA, ovvero il posto in cui sono nato e in cui sono cresciuto, e poi l'altra a "casa", ovvero il posto in cui non sono nato e in cui invece sto crescendo oggi. La differenza tra queste 2 vite è sostanziale: la casa muta sempre. Al contrario la tua CASA rimane sempre la stessa. Ogni volta che dico "Mi ricordo" mi ricordo anche delle persone, o meglio, è grazie alle persone che ho incontrato che probabilmente dico che "Mi ricordo". La CASA è fantastica, è sempre lei, immutabile e sacra. Ma spendiamo prima due parole sulla casa.

Non è facile cambiare casa così tante dannate volte. Nel corso di 3 anni ho cambiato 3 vite, ogni vita è associata a persone completamente differenti, ed è quasi curioso quando certe volte le vecchie vite si sono ritrovate o sovrapposte. Eppure che cosa è che mi ha

sempre portato a cambiare casa, una dopo l'altra, a mutare radicalmente il mio stile di vita e tutto quello a cui mi ero appena abituato ? Non lo so. Non lo riesco a capire, non so se viene da me, o se mi è stato inculcato. Giuro ancora oggi me lo sto chiedendo. Quello che so è che ho avuto il privilegio di conoscere persone fantastiche. A partire da tutti i miei amici di Milano, al mio amato gruppo del BL27, a tutti i ragazzi di Polispace, ai miei pazzi coinquilini, a tutti i poveretti che si sono subiti le mie lamentele in questi anni. A tutti voi io non posso che esprimere una profonda gratitudine per tutto, per avermi fatto sentire sempre a CASA. Grazie. Un doppio ringraziamento va a questo gruppo del BL27, se oggi sto scrivendo queste parole è perche voi mi avete permesso di essere qua, chi più che voi può capire cosa significa essere all'ultima pagina di questa tesi. Grazie ragazzi. E proprio riguardo a questo BL27, ci tengo a porgere un altro ringraziamento, alla Prof. Lavagna, che con la sua esperienza ha portato me, come molti altri di questo gruppo, a guardare sempre "outside the box" e a questa Laurea.

Poi ci sono loro, tutti i miei amici che io chiamo "Olandesi", ahime non capiscono nulla di quello che sto scrivendo perchè molti non parlano Italiano. Il rapporto di amicizia che siamo riusciti a stringere in così poco tempo durante il mio soggiorno in Olanda è incredibile, la mia casa di Hoge Morwseg mi manca ancora. Mi manca quando vi cucinavo la carbonara con la pancetta di Jumbo, uno spettacolo. Ed è proprio riguardo agli amici dell'Olanda che ci tengo ad inserire anche Jorge, il mio supervisor di ESA, una persona di quelle che riescono a trattarti sempre con estremo rispetto e a portarti a dare sempre il meglio di te. Grazie per la tua saggia guida durante tutto il mio percorso in ESA.

Ma ora che sono tornato a CASA, cosa posso dire? Beh, Wow. Ogni volta che torno nel mio amato paesino porto un bagaglio di cose da raccontare che non finisce mai. Ogni volta amo condividere le mie esperienze qui, nella mia amata Via Verdi. E il motivo per cui amo condividere tutto è che le mie due famiglie che ho a CASA sono uniche. La mia famiglia di regaz di MR e di regaz ed Modna, quei pazzi che sono sempre qui e che non cambiano mai. Vi ringrazio per essere sempre qui quando torno, è incredibile come nonostante tutto voi ci siate sempre. E poi c'è la mia FAMIGLIA. Quella che vive a CASA. Quella che mi ha sempre insegnato a dare il massimo, a non fermarmi e ad inseguire i miei sogni. A voi dedico ogni briciolo di qualsiasi mio traguardo presente e futuro. Prometto che ogni momento che verrà rimarrò sempre grato a voi. Ci sono stati dei momenti di difficoltà, e non poter essere stato a CASA per viverli è stato straziante, molte volte. Ma se a CASA non ci sono stato è per poter arrivare qui oggi e permettermi dopo di tornare in qualsiasi momento di necessità. Grazie mamma e papà, grazie Niki, grazie per esserci ed aver reso tutto questo possibile. A voi dedico tutto quanto, qualsiasi cosa che passata, presente e che verrà.

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List of Acronyms

ExPeRT Exploration, Preparation, Research and Technologies

TDE Technology Development Element

GSTP Global Support Technology Programme

CS3 Cornerstone 3

ISRU In Situ Resource Utilization

ELDO uropean Launcher Development Organization

DPTD Discovery, Preparation & Technology Development programme

TMT Technology Management Tool

CM22 Council Meeting 2022

E3P European Exploration Envelope Programme

EL3 European Large Logistic Lander

GTDM Global Technology Development Map

GER Global Exploration Requirement

ESA European Space Agency

CDF Concurrent Design Facility

OSIP Open Source Innovation Platform

TRP Technology Research Programme

ESRO European Space Research Organization

SoW Statement of Work

R&D Research & Development

ITT Invitation To Tender

TEB Tender Evaluation Board

DN Direct Negotiation

KO Kick-off

ACR Activity Closure Report

ISECG International Space Exploration Coordination Group

TWG Technology Working Group

NASA National Aeronautics and Space Administration

VBA Visual Basic Application

HRE Human & Robotic Exploration

IPC Industrial Policy Committee

RO Reporting Officer

SD Sub-domain

GNC Guidance, Navigation & Control

CSA Canadian Space Agency

PB-HME HME Programme Board

ARMADILLO Acessing Resources on MArs, Drilling Ice and Looking for Life and Organics

LOX Liquid Oxygen

CH4 Methane

TRQ Technology Requirement

TEC Technology, Engineering and Quality

ISPCP In-Situ Propellant and Consumable Production

TO Technical Officer

RO Reporting Officer

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1 | Introduction

The European Space Agency is currently broken down in the 12 directorates represented in Fig.1.1. For the purpose of this thesis the Human and Robotic Exploration one (D/HRE) represents the core of the study.

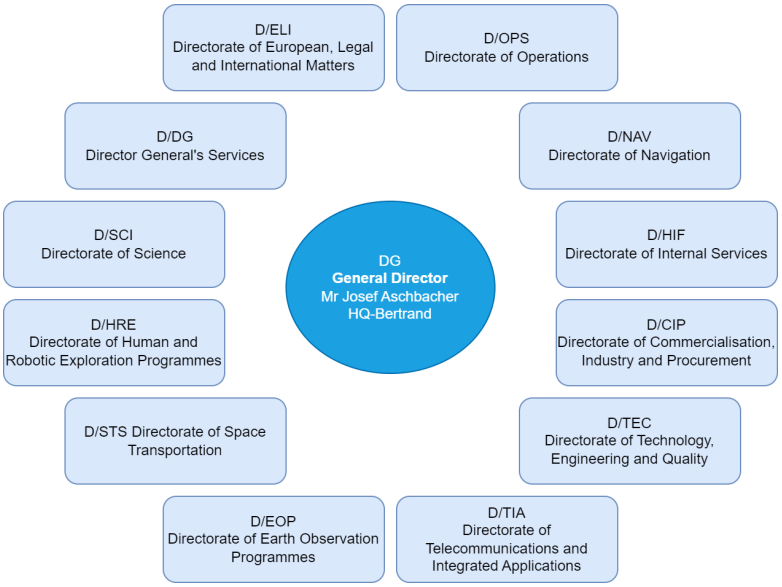


Figure 1.1: ESA directorates

ESA's vision for human spaceflight and robotic exploration is part of humanity's road to the stars. The exploration strategy includes three destinations where humans will work with robots to gather new knowledge: low-Earth orbit on the International Space Station, Moon and Mars.

In this context the European Exploration Envelope Programme (E3P) was coinceived, named Terrae Novae in 2021, approved by Ministers at the Ministerial Council in Lucerne in December 2016 [38].

The E3P programme includes 6 main activities (Fig.1.2): ExPeRT element, SciSpacE and 4 Cornerstone campaigns (Humans in LEO, Humans beyond LEO, Lunar Robotic Exploration, Mars Robotic Exploration).

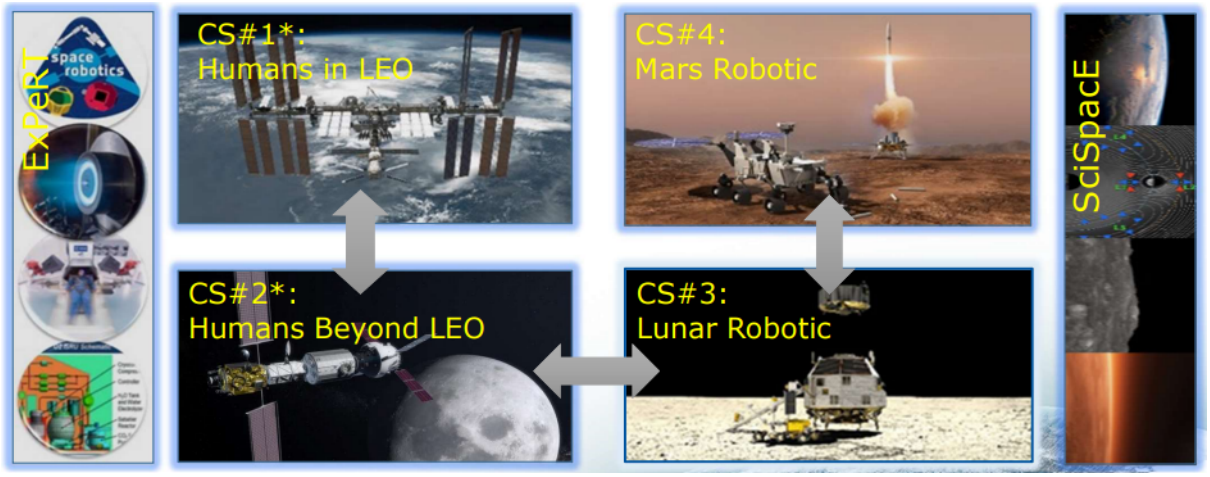


Figure 1.2: E3P Future Programme [16]

Programme highlights include regular astronaut missions to the International Space Station; Europe's contributions to Artemis including the European Service Modules for Orion and two of the four main elements of the lunar Gateway; and a multi-decade exploration of the Red Planet through ExoMars and Mars Sample Return. Exploration missions require an unprecedented mission complexity and knowledge, achieved through systems design by means of brand new technologies and capabilities. In this framework the ExPeRT (Exploration Preparation, Research and Technology) team was created.

1.1. HRE-E (ExPeRT Team)

ExPeRT (logo represented in Fig.1.3) is part of ESA's European Exploration Envelope Programme (E3P) [36].

Figure 1.3: ExPeRT Team logo [36]

It integrates, coordinates, and manages the development of studies and technologies for future Exploration missions to LEO, Moon and Mars destinations, and being ExPeRT an element of the E3P, part of its yearly budget is allocated to the team. The investment and

exploration budget breakdown of Fig.1.4 shows the allocated budget available to ExPeRT as output of the CM22.

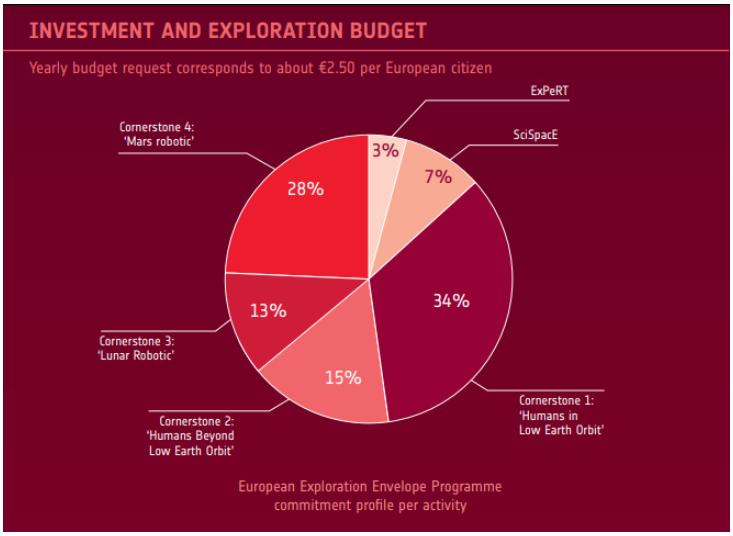


Figure 1.4: E3P investment and exploration budget breakdown [37]

The technology preparation operated by the team is essential to position Europe for upcoming opportunities with various partners expected in the next few years.

The objectives of ExPeRT are to:

- ensure that future exploration missions, projects and associated technologies are well prepared and de-risked;
- facilitate the selection process of new exploration missions and projects by providing the adequate maturity for system definition and technology readiness;
- establish new collaborations with international partners (both existing and emerging) to create future exploration opportunities;
- identify European leadership and enable autonomous capability.

ExPeRT therefore:

1. implements architecture and mission definition studies for exciting and inspiring new robotic and human missions and associated vehicles and infrastructure elements;
2. prioritises and oversees early development of technologies needed for future exploration missions up to a sufficient maturity, in terms of TRL, for implementation;
3. assesses the scientific, technological and overall benefits of missions and projects to be proposed for implementation;

4. explores new opportunities for cooperation in space exploration with established international partners as well as new ones.

ExPeRT oversees mission feasibility and system definition studies for all exploration activities. It is responsible for the implementation of technology activities with an aim of reaching a technology readiness of TRL 5 prior to the start of mission implementation and it will work in partnership with ESA's Directorate of Space Engineering and Technology (refer to Fig.1.1) on defining low TRL exploration-related technology activities to be carried out in the Technology Development Element (TDE) of the Discovery, Preparation and Technology Development (DPTD) programme.

1.2. Context of the Thesis

Among the four main tasks for which the team is responsible, the thesis minly focuses on the second one, dealing with the technology development of low TRL technologies in order to reach the required TRL for flight (but as will be explained interactions are present also with the other tasks of the team). Acting as an European agency, ESA is taking care of the technology development; at this purpose different programs and entities are involved. Each of them is addressed by different teams and directorates, presenting their own life-cycle for the technologies maturation.

In the specific case of ExPeRT, the team follows a life-cycle which brings the tech-

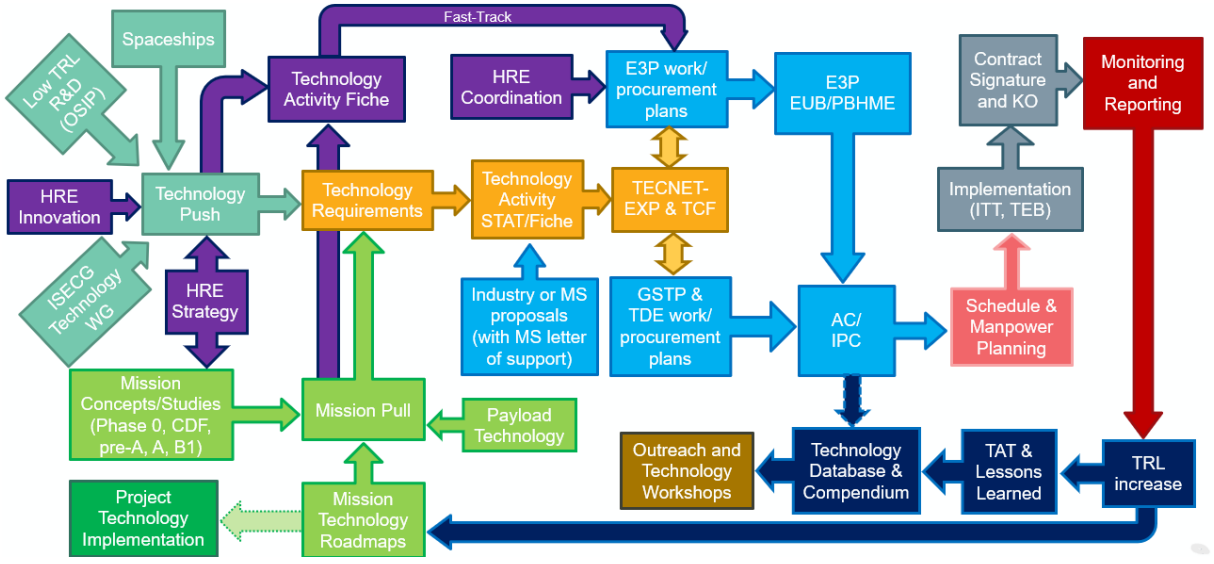


Figure 1.5: ExPeRT Technology Process Flowchart [3]

nologies from their definition up to the TRL maturation and update of the exploration compendium which is represented in Fig.1.5. The flowchart is the core the thesis, repre-

senting its foundation.

From a quick overview it can be noticed how the the flowchart involves numerous steps; this is caused by the inter-exchange between different directorates and personnel which is required for the contracts management and proper technology activity definition: despite this flowchart is "internal" to the team, in the life-cycle of a single technology maturation the responsibility jumps between entities, each of them addressing single tasks at the purpose of fulfilling the whole process.
Although the steps of the process are well defined, the slow "bureaucracy" needed to develop a single cycle of technological development caused by the continuous bounce of information between the various responsible entities results in a system of great complexity, difficult to monitor and track.
The thesis is therefore investigating the possible optimization of the whole end-to-end technology process, resulting in smooth tracking, enhancing of the coordination between the involved entities and empowering of the technology process in term of time reduction and awareness of the development stages.
At this purpose the thesis will present the whole process from deep study of the problem to the proposed developments and their implementation: the proposed "solution" to enhance the coordination and monitoring of the whole process is in the form of an ad hoc platform, which has been named Technology Management Tool (TMT).

Technology Readiness Level

The concept of TRL is introduced. Technology readiness levels (TRLs) are a method for estimating the maturity of technologies during the acquisition phase of a program. TRL is determined during a technology readiness assessment (TRA) that examines program concepts, technology requirements, and demonstrated technology capabilities [40]. TRLs are based on a scale from 1 to 9 with 9 being the most mature technology [15]; the TRL scale is presented in Tab.1.1.

In the context of this thesis the term "low TRL" technologies will be used, referring to the TRL levels which go up from 1 to TRL 5/6, it is in fact up to this level that the R&D programs in objective are mainly operating.

1.2.1. Privacy

Due to privacy ESA is preventing the publication of sensible data. Given the framework of project management in which the thesis is moving, some information are available to ExPeRT before they can be published, and the tools and cycle in objective of the thesis

TRL Scale	Technology Readiness Level
1.	Basic principle observed and reported
2.	Technology concept and/or application formulated
3.	Analytical and experimental critical function and/or characteristic proof-of-concept
4.	Component and/or breadboard functional verification in laboratory environment
5.	Component and/or breadboard critical function verification in a relevant environment
6.	Model demonstrating the critical functions of element in a relevant environment
7.	Model demonstrating the element performance for the operational environment
8.	Actual system completed and accepted for flight ("flight qualified")
9.	TRL 9 Actual system “flight proven” through successful mission operation

Table 1.1: TRL Scale

are also embedding these information.
For the purpose of the thesis only publishable data are used; the reader is therefore invited to consult the published document in reference on the ExPeRT website [36].

There are two main strategies used to deal with data protection. In the case where sensible data is involved in the description of the processes and methodologies, fictitious information are assumed, and the reader is properly notified when this occurs. [1] In the case where instead graphics involving protected information must be shown, blurred images are employed to cover the sensible data.

1.3. Thesis Outline

The thesis will present the detailed steps which brought to the implementation and utilization of TMT, with practical examples and "results" obtained. The content of the thesis can be split in three main parts:

1. study of the problem: in-deep study of the Technology Process Flowchart interconnections (between the boxes of Fig.1.5) and consequent understanding of the responsibilities and tasks involved;

[1] The fictitious information used to replace the protected data is assumed to be reasonable and coherent to the purpose of the thesis.

2. solution set up in terms of ad hoc platform and proposed modifications to the current strategies, instruments and processes;

3. evaluation of the results obtained in terms of outputs of the platform and ISRU technologies adopted as user case for the publication of the results.

The thesis is organized in 5 chapters.
Chapter 1 is devoted to the global understanding of the framework inside which the thesis is developed, introducing the European Space Agency and the scope of ExPeRT as an organ of the E3P. The scope is then explained in detail in Chapter 2, together with the entities involved and the step-to-step procedures which bring an activity from the beginning of the flowchart up to the end (even though the flow is presented via a loop, a "start" and an "end" will be identified). In Chapter 3 the main objective is represented, with the architecture and development explanation of TMT and embedded Exploration Technology Database. At this purpose practical examples and outputs obtainable thanks to the platform are depicted in Chapter 4, applying the full technology process to the In situ Resource Utilization user case with consequent generation of the ISRU roadmaps. The conclusion of the work is presented in Chapter 5, together with limitations, future developments and suggestions for coordination enhancing. Finally, Appendix **??** shows the cross-cutting challenges European ISRU Roadmaps.

2 | R&D Activities for Exploration

In section 1.2 the Technology Process Flowchart has been introduced. The purpose of this chapter is to provide a detailed explanation of the full framework of the chart, from the definition of the technology activities to outreach of the results obtained, the tools and the entities involved in the management/coordination of the flow.

In the context of exploration, the act of investigation of the unknown requires unprecedented capabilities. To this extend ESA strategy for the E3P includes a variety of missions and technology developments to be carried out, as to fulfill the technology gaps required for the achievement of the milestones.
It can be said that ExPeRT is subdivided into 2 main areas: mission studies and technologies.

2.1. Mission studies

Regarding the mission studies branch, ExPeRT implements architecture and mission definition studies for exciting and inspiring new robotic and human missions and associated vehicles and infrastructure elements. In order to understand the mission implementation lifecycle the concept of Concurrent Design Facility is introduced.

2.1.1. CDF

Traditionally, engineers faced with the task of designing a new, complex system or architecture work in sequence, one step at a time, passing the design from one subsystem specialists to the next without interaction with the rest of the team. The Concurrent Design Facility (CDF) enables "concurrent engineering" based on teamwork and focused on a common design model that evolves iteratively in real time as the different subsystem experts provide their contributions [39].
The CDF consists of four design rooms and a number of support and ancillary rooms grouped around a central foyer; the layout of the CDF main room is represented in Fig.2.1.

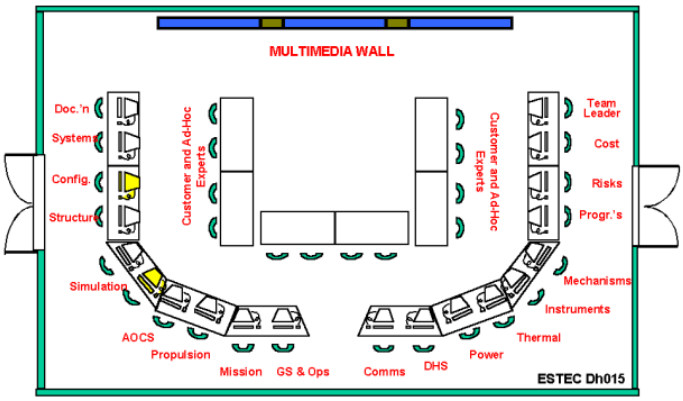


Figure 2.1: ESA/ESTEC Concurrent Design Facility Layout [1]

At the end of the design sessions a technical report is produced. The report includes the mission explanation, its architecture and the subsystem analysis. Among the output also the mission requirements and technologies TRL are produced.

2.1.2. Mission phases lifecycle

In order to understand the ExPeRT mission definition lifecycle the concept of mission Phase is introduced. A quick overview of the typical space project lifecycle phases according to the ECSS is shown in Fig.2.2.

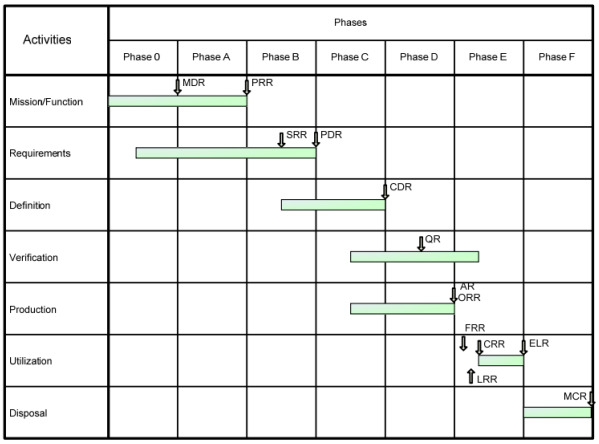


Figure 2.2: Space Project Lifecycle [14]

The "CDF step" in the mission design is corresponding to the Phase 0 in the chart (or Pre-Phase A according to NASA glossary [45]).

2.1.3. ExPeRT Mission study lifecycle

During 2020-2022, the ExPeRT team conducted a series of ESA internal studies at its Concurrent Design Facility and created a portfolio of mission concepts for potential future Moon [46] and future Mars [47] exploration. These studies involved a team of experts in the various engineering and technology fields of expertise at ESA. They enabled the initial analysis of the mission objectives and identification of the architecture/system needs in order to achieve them. This was performed to inform the planning for the Terrae Novae strategy roadmap and its notional mission roadmap, and also to identify technology requirements for early developments.
Starting from the conceptual definition of the mission, the CDF study is run with the consequent generation of the CDF report, corresponding to the Phase 0. The further development in the mission study are then assigned to the companies by ITTs, until the missions reach then the phase B1, which is still conceived as the last stage of the conceptual part of the mission design.
The prioritization of the missions from the portfolio is then run, bringing to the selection of one or two of them to be approved for successive development (from phase B2 to fly). The prioritization is required as the budget for further developments is in fact only sufficient for part of the portfolio.

2.2. Technology Activities

As it was jut explained, besides the mission definition and implementation, the technologies represent a core part of the development activities. The technology activities are used in order to increase the TRL of the exploration technologies and reach the required one for flight.

2.2.1. ESA R&D Programs

Within ESA the technologies are developed under several corporate and domain specific programmes and initiatives done in partnership with industry, academia and research centres. Together with ExPeRT several other programmes operate as R&D.

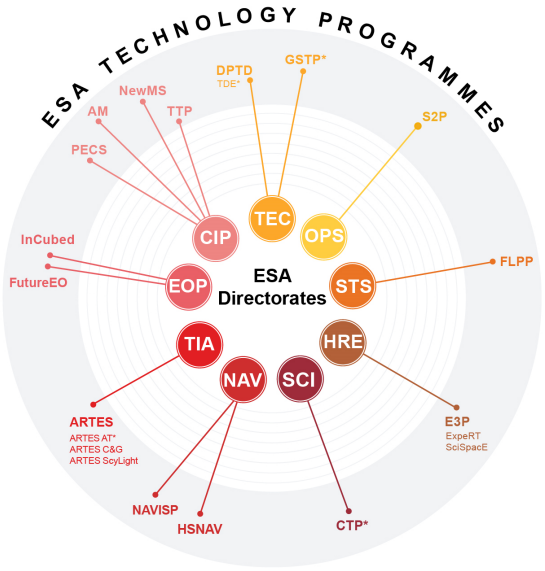


Figure 2.3: ESA technology programmes [41]

In Fig.2.3 the ESA technology programmes are presented. Among these, the main one relevant for exploration purposes are shown in Tab.2.1 together with the TRL range in interest.

TRL scale	Technology Programmes			
9			■	
8			■	
7			■	
6		■	■	■
5		■	■	■
4	■	■	■	■
3	■	■	■	■
2	■		■	
1	■			
	TDE	MREP	GSTP	ExPeRT

Table 2.1: ESA TRL scale per programme

It is important to highlight that this is not the exhaustive list of technology programmes which are addressing the exploration domain (in fact others are present and included in TMT), but they represent the majority of the activities. A short description of the

technology programmes in objective is given hereafter [5].

ExPeRT

Within E3P Period 1 (2017-2019), ExPeRT has already coordinated technology activities based upon those funded in the Discovery, Preparation and Technology Development (DPTD) element of Basic Activities and benefiting from the related technical infrastructure and laboratories. Similarly, Period 2 (2020-2022) it is used to implement technology activities that aim at a TRL 5 prior to the start of Phase B2 of the applicable projects. This activity will be done in partnership with the ESA Directorate of Technology, Engineering and Quality (D/TEC) by defining low TRL exploration related technology activities carried out in the DPTD element of Basic Activities and/or complementing technology activities performed in the GSTP programme. The rationale for aiming only for TRL 5 at end of Phase B1 is that phase B1 is still part of the competing period with more than one Prime involved in the mission study. The Primes could have different architectures based on different technical solutions therefore asking them to reach TRL 6 for critical technologies at the end of Phase B1 could be considered excessive in terms of economic resources. Additionally, the need to reach TRL 6 only at the end of Phase B2 will give to the selected Prime for phase B2/C/D the possibility to assess different technologies and choose, in accordance with the Agency, the best ones for further adoption in the project.

TDE

TDE represents the Technology Development Element of ESA's Discovery, Preparation and Technology Development (DPTD) Basic Activities. It supersedes the Technology Research Programme (TRP) and the European Component Initiative (ECI). The TDE is organised similarly to TRP and pursues the same objectives. It is a technology programme which addresses low TRL technologies, with the aim of fulfilling both pull ans push requirements. It is the decision base for technology feasibility of the agency, being funded by part of the ESA mandatory budget.

GSTP

GSTP is indeed carried out since 2016 as a continuous programme with regular review points every three years and concurrently with the Ministerial Conferences. At these occasions, Participating States are invited to confirm the continuation of the programme activities together with the associated conditions and to increase their financial contributions to the programme. It is addressing technology programme not application-specific,

covering all applications domains (except Telecommunications) as well as generic technologies (technologies for multiple applications). Spans from low TRL to qualification, as well as provision of flight opportunities. It is based on continuously updated Work Plans, approved by representatives of the Participating States.

MREP

Established before the creation of E3P and conducting mid-TRL activities, the MREP programme is now approaching its completion. The MREP work plans were defined with the objective to reinforce Europe's position in Mars robotic exploration and prepare for a European contribution to a future international Mars Sample Return (MSR) mission. Driven by the exploration of the Red Planet and with Mars Sample Return as the long-term target mission, it was divided into candidate missions and technology categories.

2.2.2. Categorization per Technology Area

Among the countless applications and internal breakdown that can be used to subdivided the technologies relevant for exploration purposes, an ExPeRT internal categorization has been performed (see fig.2.2 [36]). This is really useful in order to subdivided the categories per "area" and have a breakdown which is fulfilling the most common subsystems/application/branches of the space engineering domain.

2.2.3. Fiches and Work/Procurement Plans format

The data format and templates for the requirements and activity fiches are presented. It's important to note that as the templates are subjected to continuous update, the current status represents the last update (E3P Period 2).

Requirements Formulation

ExPeRT formulates the technology needs in the Exploration application domain at ESA categorizing the requirements under two possible types: technology-push or mission-pull requirements.

Mission Pull Requirements A "mission-pull" activity responds to a specific identified exploration mission need and requirements are derived from completed mission concept/system studies in the Directorate of Human and Robotic Exploration. They can be either formulated by ExPeRT technology engineers or from the CDF reports, highlighting the lowest TRL technologies. The process for the definition of exploration mission-pull

ExPeRT Technology Areas
1. Propulsion
2. Novel Energy Systems
3. Robotics and Mechanisms
4. Artificial Intelligence Applications
5. Advanced Life Support Systems
6. In-Situ Manufacturing
7. Crew Health Management
8. Space Resources Utilisation
9. Radiation Protection & Environmental Effects
10. Communication and Navigation
11. Subsurface Sampling/Deep Drilling
12. Guidance, Navigation and Control
13. Avionics
14. (re-)Entry, Descent and Landing
15. Thermal Control Systems
16. Mission Operations Data Systems
17. Others

Table 2.2: ExPeRT Technology Areas

technology requirements is repeated each year, see in Ref.[4] the updated list of 2022.

Technology Push Requirements A "technology-push" activity for exploration is expected to result in a step-change or breakthrough (disruption) in a technology that may, in the future, facilitate exploration, but is not driven by a mission requirement or "mission-pull" already identified. Moreover, it is intended to foster innovative ideas from technical experts and allows high-level performance targets to be considered. It can be also implemented based on the ESA position toward the Global Exploration Roadmap.

Both push and pull requirements present the same template; the name of the "format" used technology fiche, expressed through its acronym TRQ. There are two main templates that can be used: one is used as "internal" to ESA, therefore in use during its drafting, while the "public" template follow substantially the same logic, containing less information available for the public. The internal template is presented in Tab.2.3.

The data to be fetched belongs to the blank squares in the table, with the relative information explained. For the purpose of the thesis it is important to spend some words on the *TRQ Reference*: each requirement is univocally identified by this code. It is the only box inside the fiche that is not subjected to variation [1] along his drafting/development.

[1] Also others boxes are not supposed to change, but this represent the pre-defined acronym univocally assigned to the TRQ.

Requirement title header					
TRQ Reference:	[Mission study acronym-technology area number-sequential number]				
Title:	(refer to mission-pull requirement)				
Description:					
(provide mission introduction/background, propose high-level technology target, define and justify the requirement)					
Technology Heritage:					
(for completed activities)					
Any similar developments taking place within or outside of ESA:					
(for running activities)					
TRL Date (for TRL5):		**Technology Area:**	(1-17)	**Technology Area Description:**	(area title)
Mission Application:		**Added By (name):**		**Data Provider (mail-code):**	
ROM Cost (kEuro):		**Expression of interest:**	(expected TEC/OPS involvement)		

Table 2.3: ExPeRT Internal Requirement Template

By means of the reference the requirements can be then identified and addressed.

Activity fiche

For what concerns the technology activities, similarly to the requirements templates also the activity ones are formatted as fiches. It is therefore immediate to collect information regarding each activity having a look to its fiche.
Unfortunately, given the different programmes also belonging to different directorates, the templates between each programme is slightly different, resulting in different fiches, in fact the procurement cycle for each programme can be different by the one presented for ExPeRT. This difference is one of the main objectives of the thesis, in fact as will be addressed in Chapter 3 the harmonization of the data is fundamental for a global tracking and efficient monitoring.
The ExPeRT fiche for period 2 (the triennium 2019-2022) is reported in Tab.2.4.

Following the same logic as for the requirements (Section 2.2.3) each technology activity is identified by one programme reference, which is in the form of a univocal alphanumeric code for each of the activities.
It is crucial to maintain a clear distinction between these references as each of them is directly linked to one full development cycle for one R&D activity.

<table>
<tr><th colspan="6">E3P Activity Fiche</th></tr>
<tr><td>Title:</td><td colspan="5">XXXX</td></tr>
<tr><td rowspan="3">Activity Area:</td><td colspan="2" rowspan="3"></td><td>Programme Reference:</td><td colspan="2">To be provided by HRE-C</td></tr>
<tr><td>Work Plan Reference:</td><td colspan="2">Specify high level activity as referenced in Work Plan</td></tr>
<tr><td>Category</td><td colspan="2">Category identified for this activity in the current version of the Work Plan</td></tr>
<tr><td>Total Budget (K€):</td><td colspan="5">XXXX</td></tr>
<tr><td colspan="6">Objectives</td></tr>
<tr><td colspan="6">One paragraph describing the objectives of the activity.</td></tr>
<tr><td colspan="6">Description</td></tr>
<tr><td colspan="6">Text containing the background and description of the proposed activity. Length should be between ½ page for small activities (<500K€) and up to 2 pages for bigger activities (>500 K€). Ideal is 1 page.</td></tr>
<tr><td colspan="6">Deliverables</td></tr>
<tr><td colspan="6">Precise description of deliverables, including models (EM, QM, etc.), software, test results, documentation.</td></tr>
<tr><td>Current TRL:</td><td>X</td><td>Target TRL:</td><td>Y</td><td>Application Need Date:</td><td></td></tr>
<tr><td>Application Mission:</td><td colspan="2">Name of mission(s) where the results of this activity will be used.</td><td>Contract Duration (months):</td><td colspan="2"></td></tr>
<tr><td>Procurement Type</td><td colspan="5">Explain in a sentence the procurement approach: continuation of existing contract, open competition, AO, etc.</td></tr>
<tr><td>Proposed Contractor(s)</td><td colspan="5">Proposed contractors, if any, consistent with the proposed procurement approach.</td></tr>
<tr><td>Procurement Policy:</td><td colspan="2">(C, C(R), DN/S, DN/C)</td><td>S/W Clause:</td><td colspan="2"></td></tr>
<tr><td colspan="6">Consistency with Harmonisation Roadmap and conclusion:</td></tr>
<tr><td colspan="6">This field is only for technology activities which are coordinated with TECs part of the Harmonisation process. N/A otherwise.</td></tr>
<tr><td colspan="6">Remarks:</td></tr>
<tr><td colspan="6">Use this field for any information you consider relevant, but does not fit in any of the above fields.</td></tr>
</table>

Table 2.4: ExPeRT E3P Activity Fiche

Work and Procurement Plans

In order to implement the proposed technology activities, ExPeRT is collecting the corresponding fiches in the Work Plan documents. The Work Plan documents are Word/PDF

documents which contain the list of activity fiches. The Work Plans are then submitted to the member states, and the fiches which are approved are then inserted in the Procurement Plans, representing the same format, but containing only approved fiches. In general all the Work and Procurement Plans prepared are univocally identified by an acronym (following the example of the fiches). In Section 4.1 a practical example of how the fiches are attributed to the Work Plans is shown.

Exactly the same logic as per programme reference is applied to the Work Plans and Procurement Plans reference. Each Work Plan prepared by ESA is univocally identified by one alphanumeric acronym, so that each acronym can address one, and one only, Work Plan (same for the Procurement one). An example of Work and Procurement Plan reference is given in Tab.2.5.

	Document Reference
Work Plan	ESA/PB-HME(2020)10, rev.13
AC Proc. Plan	ESTEC AC 529-34
IPC Proc. Plan	ESA/IPC(2022)125,rev.1

Table 2.5: Work and Procurement Plans reference examples

2.2.4. Sharepoint and PRONTO Tool

ExPeRT uses the team Sharepoint as platform for collaborative environment. In 2020 the PRONTO Tool has been introduced and embedded within ExPeRT sharepoint: PRONTO is developed as an HTML platform, listed inside Sharepoint, directly accessible or shareable via link to external users. PRONTO is the platform used by the team for data upload and monitoring of the ExPeRT contracts; it collects all the ExPeRT activities and the correlated procurement steps and development progress. The details on how PRONTO is used and which are the steps involved in the procurement of an activity are given in Section 2.3.2.

Each of the approved activities is loaded on the platform, which contains mainly 6 sections of importance:

1. technology fiche: the data contained in the fiche in PRONTO are the same of the real activity;
2. assigned personnel: the subsection dedicated to the upload of the people's name who have been assigned to the activity;
3. implementation steps: contain the implementation steps and relative dates of the contract associated with the activity;

4. contractors: collect the contractors and sub-contractors associated with the activity, together with relative country and budget allocated;
5. milestones: milestones names and infos associated with the contract of an activity, together with the associated dates and achievement status;
6. quarterly reports: it's the collection of the quarterly reports associated with the activity, therefore the ongoing status of the development quarterly reported on the platform.

The PRONTO window together with the respective sections (1 to 4) are shown in Fig.2.7, while the milestones windows in depicted Fig.2.6.

Milestones						
Title	**Milestone Name**	**Contract Date**	**Planned Date**	**Actual Date**	**Amount (kEuro)**	**Achieved?**

Table 2.6: PRONTO Milestone window

2.3. R&D Activity Lifecycle

Now that the fiches and Work Plans (representing the subjects of the life-cycle) have been introduced, the detailed cycle is explained. The ExPeRT technology flowchart in Fig.1.5 has been further developed in Fig.2.4 by means of draw.io tool [52]. This version is including both the entities involved and the high level functionalities/tasks in the procurement and implementation steps.

Given the high amount of technology activities to be developed to fulfill the needs for future missions implementation, the budget per se is not sufficient for all the technology implementations. ExPeRT is therefore working side-by-side with TDE program in order to define the technologies and utilize TDE budget for implementation of part of the R&D activities. This results in two main distinct cycles that the technologies in their formulation side can have; both of them are included in Fig.2.4.

ExPeRT Direct Implementation Founded by its own yearly budget ExPeRT can directly implement the "fast track" for the R&D activities, still coordinating and presenting the activities with the TECNET forum, but not undergoing the classical definition of requirements as an intermediate step, and therefore passing from the mission/technology needs to the activity fiche draft directly.

Activity Fiche				
Activity title				
Activity Status				
Objective				
Description				
Deliverables				
Reference			**Programme**	
Budget (kEuro)	**Total**	**E3P**	**Technical Officer**	
Duration (months)			**HRE Interface**	
Contract Number			**Project Controller**	
Mission Applicability			**Contract Officer**	
Procurement Policy			**TEC Support**	
IPC Reference			**Reporting Officer**	
PB Reference			**TRL Start**	
Proposed Contractor(s)			**TRL Target**	
S/W Clause				
Remarks				
Justification for DN				
Consistency with Harmonisation Roadmap and conclusion				
Notes for PRONTO				
Contractors				
Type	**Name**		**Country**	**Amount(k€)**
Implementation				
	Contract	**Planned**	**Actual**	**Achieved?**
Draft SOW Delivery				
Pre-TEB				
ITT (RFQ) Issue				
ITT (RFQ) Close				
TEB				
Negotiation				
KO				

Table 2.7: PRONTO reporting tool template

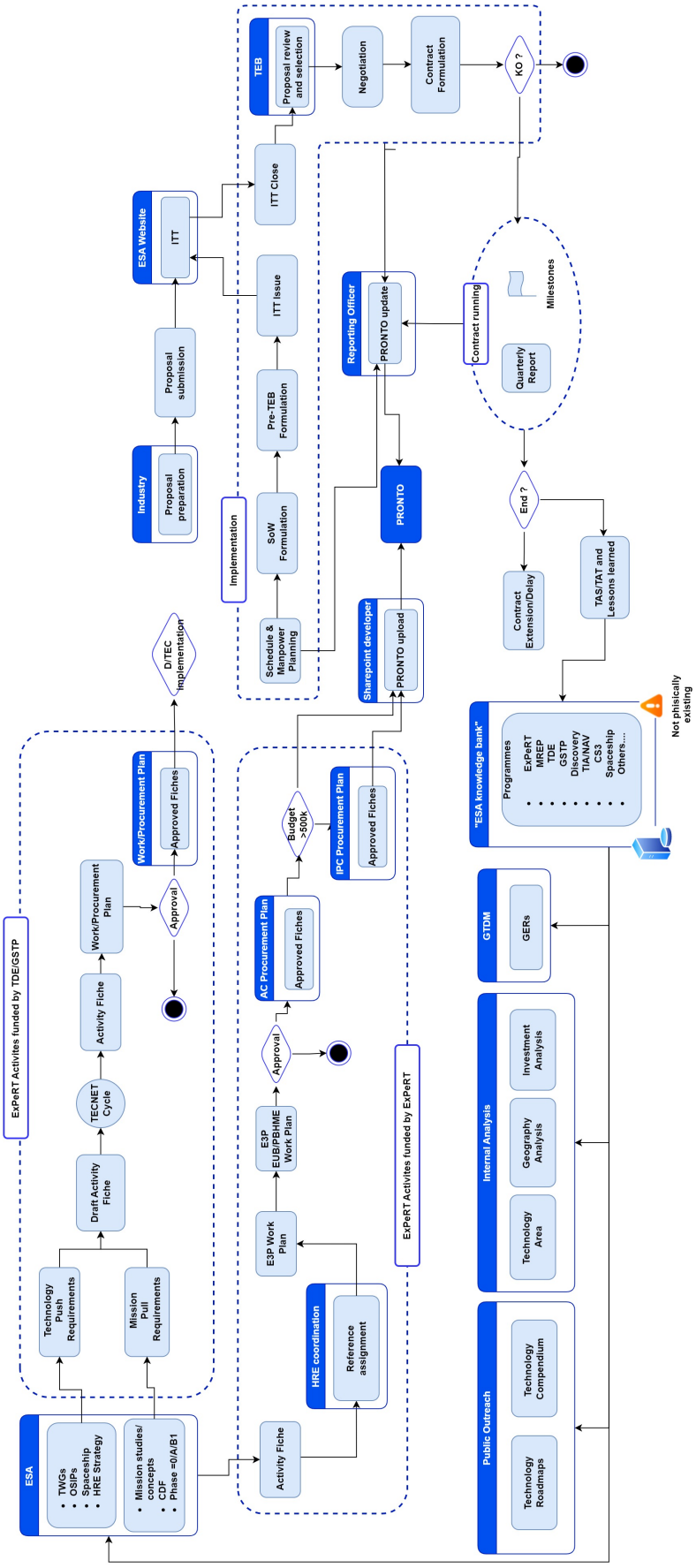


Figure 2.4: Detailed ExPeRT Technology Lifecycle

Activities Nominal Cycle The nominal cycle (followed by TDE activities) is passing through the TECNET, therefore it is subject to experts revision of the requirements, assessment of internal activity proposals and recommendation for approval.

Flowchart decomposition

To study the problem in detail, it is necessary to simplify the whole process, analyzing the individual steps that lead from one stage to another of the cycle. To this purpose the full workflow has been broken down into his min constituent parts. Four main steps have been identified in the overall ExPeRT Technology Flowchart:

1. procurement;
2. implementation and contract KO;
3. monitoring and control of the R&D activity;
4. storage of the developed technologies and consequent public outreach.

Each of the four constituent parts is analyzed below.

2.3.1. Procurement cycle: from requirements to Implementation

The in-deep analysis of the initial steps of the whole cycle are presented in Fig.2.5.

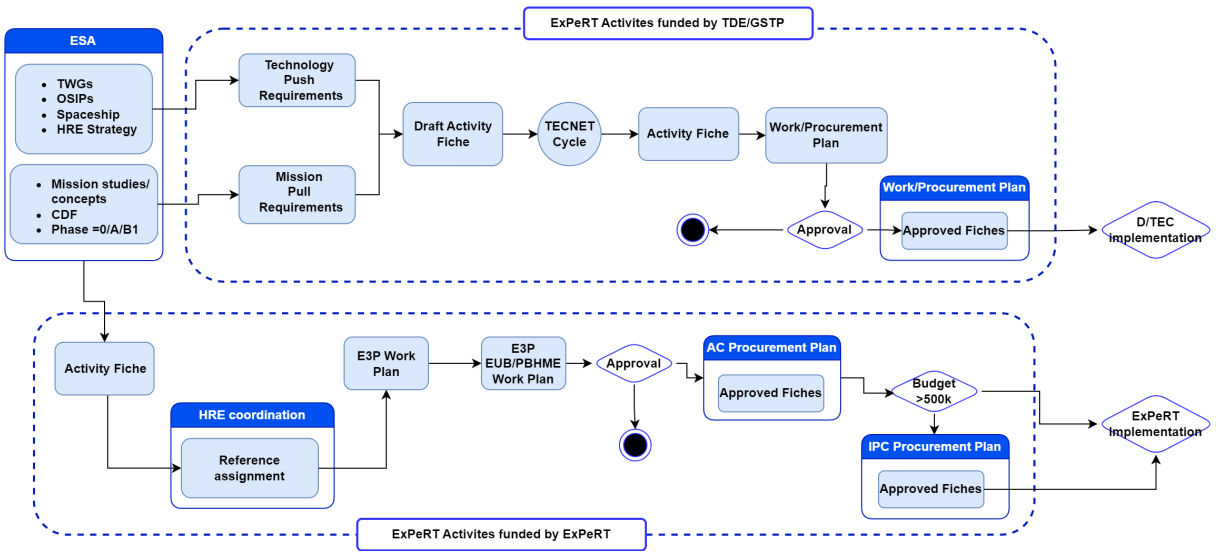


Figure 2.5: ExPeRT definition and procurement cycle

Starting from the left of the figure, there are two strategies that ExPeRT can follow:

1. direct formulation of the activity fiche funded by its own budget (bottom part of the graph);
2. formulation of the requirements (both push and pull) and usage of D/TEC budget for implementation of TDE/GSTP activities (upper part of the graph).

In both strategies the formulation of the requirement/activity fiches is made from different inputs (top left conrner of Fig.2.5), in fact the R&D programmes answer to different missions/technology needs as well as technology push requirements to enable new capabilities.
For TDE-funded activities ExPeRT together with the D/TEC colleagues is formulating the draft fiche, which are then subjected to the TECNET cycle, with the consequent updated formulation.
The TECNET consists of several working groups of technology experts from ESA technical and programme directorate [53]. The forum is responsible for revision of technology requirements, evaluation of activities proposals, recommendation of activities and monitoring of the implementation, among other responsibilities.
The fiches are then integrated in the TDE/GSTP Work/Procurement Plans, and after approval by the Industrial Policy Committee (IPC) they are implemented by D/TEC; not all the activities are approved, in fact only part of the Work Plan fiches is included in the IPC Procurement Plan. The HME Programme Board (PB-HME), and the Industrial Policy Committee (IPC) are the member states delegate bodies which operate in the context of the approval of the ESA activity proposals, acting as "judge" for the proposals.

Focusing on ExPeRT (note that ExPeRT is also responsible for managing the MREP and CS3 technology related activities for the E3P2), once the activities are directly formulated and approved they are inserted in the quarterly E3P workplan (one per each quarter) by the HRE coordination office; the reference both to the activities and to the work plans are assigned by them. They are then presented to the delegation in the PB-HME, and upon approval the procurement plans are submitted before to the Adjudication Committee (ESA internal body of senior management), and lastly to the IPC. Depending on the budget the activities can then undergo the IPC level or not.[2]

The ExPeRT activities funded by D/TEC have support from an HRE interface for their implementation, while the one funded directly from ExPeRT are already under ExPeRT implementation, and they are loaded to PRONTO (the next paragraph will explain this step).

[2]The budget information is a sensitive information and cannot be introduced.

2.3.2. Implementation and KO

Once the IPC has been approved, there is a main distinction between D/TEC activities and ExPeRT: while D/TEC activities are being monitored within Actis2 platform under TEC domain, ExPeRT one are loaded to PRONTO; the thesis is therefore addressing only the latter one.

Upon IPC approval, the activities undergo a procurement cycle which start with the approved fiches planning and ends with the KO of the contract for its implementation. The whole process is shown in Fig.2.6.

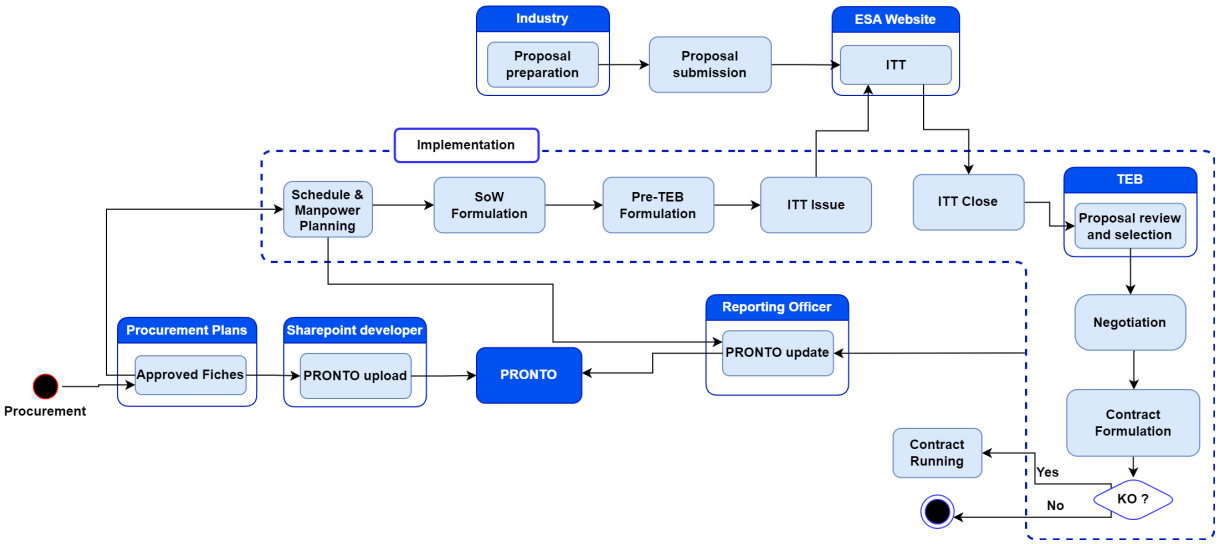


Figure 2.6: ExPeRT implementation cycle

Firstly, an ExPeRT technologies coordinator is sending the approved fiches from the Procurement Plan to the PRONTO developers, responsible of uploading the fiche on PRONTO. From now on, the approved activities are therefore present within the PRONTO list in ExPeRT Sharepoint.
From now on the procurement cycle begins: ESA operating as an agency is opening Invitation To Tenders (ITTs) to which company can apply in order to win and implement the contracts.

From the description of the activity in the fiche (see Fig.2.4) the Statement of Work (SoW) is written and the first idea on the Tender Evaluation Board (pre-TEB) composition is formulated (the TEB is the judge of the ITT). The activity is therefore ready to be published, and ESA opens an ITT (ITT issue) on ESA website. Once the deadline is reached, the ITT is closed and the effective TEB is formulated. Operating as judge the TEB selects the winning company and the negotiation begins. The terms of the contract

are then discussed until the contract is signed and the KO date is set. The process described above represents the most general procurement cycle, but there can be several types (Fig.2.8). The type of procurement is already part of the fiche since the beginning (see Tab.2.4).

Procurement Type	Description
C	The tendering for the companies is open to any company belonging to the ESA member states.
C1	Activities in open competition limited to the non-Large-System Integrators.
C2	Activities in open competition, where a significant participation of non-LSIs is requested.
C3	Activity restricted to SMEs & R&D organisations, preferably in cooperation.
C4	Activities in open competition, subject to the SME subcontracting clause.
C(R)	Competition is restricted to a few companies, indicated in the \emph{Remarks} column.
DN/S	The contract will be awarded by direct negotiation in implementation of a defined industrial policy or resulting from a sole supplier situation.
DN/C	The contract will be awarded in direct negotiation being the continuation of a previous activity with the same contractor.

Table 2.8: ESA Procurement Types

There is not a fixed term for what concerns the procurement cycle timeline, but for the purpose of the thesis as an example is assumed [3] 32 weeks for the open competition contracts (C-types of procurement) and half of it (16 weeks) for the DN-types (the DN doesn't imply the ITT opening being the company directly selected as only tender). The detailed steps timeline is shown in the figure.

All this process has to be monitored and reported in PRONTO. At this scope the Reporting Officer represents the interface between the contract and ExPeRT, being the responsible for reporting on the tool. Along with the overall procurement, the activity status has to be changed within PRONTO, from *In Preparation*, corresponding to when the activity has been just approved, the status is set to *In Procurement* the contract is signed and finally to *Running* when the KO is reached. Despite other personnel is involved in the whole procurement cycle, for the purpose of the thesis only some are described: the Technical Officer (TO) is responsible for the generation of SoW and its requirements,

[3]This is not the effective ESA Procurement Cycle timeline, it is just an assumption. The effective time is protected by ESA privacy policy.

propose the TEB nomination for the associated ITT, secretary of the TEB, technical management of the contract, reporting to the Team Leader and closing the activity in accordance with this procedure; the Contract Officer validates the TEB nomination for the associated ITT, is the secretary of the TEB, takes care of the contractual management of the contract; and finally the Project Controller is responsible for establishing Cost at Completion, supporting the ExPeRT Team with respect to financial control and reporting, support the ExPeRT Team with respect to planning of the implementation schedule for newly approved activities.

2.3.3. ExPeRT Monitoring and control

Once the KO is reached, the activity status is set to running and the implementation of the activity begins. Fig.2.7 depicts the flowchart from the KO for this phase.

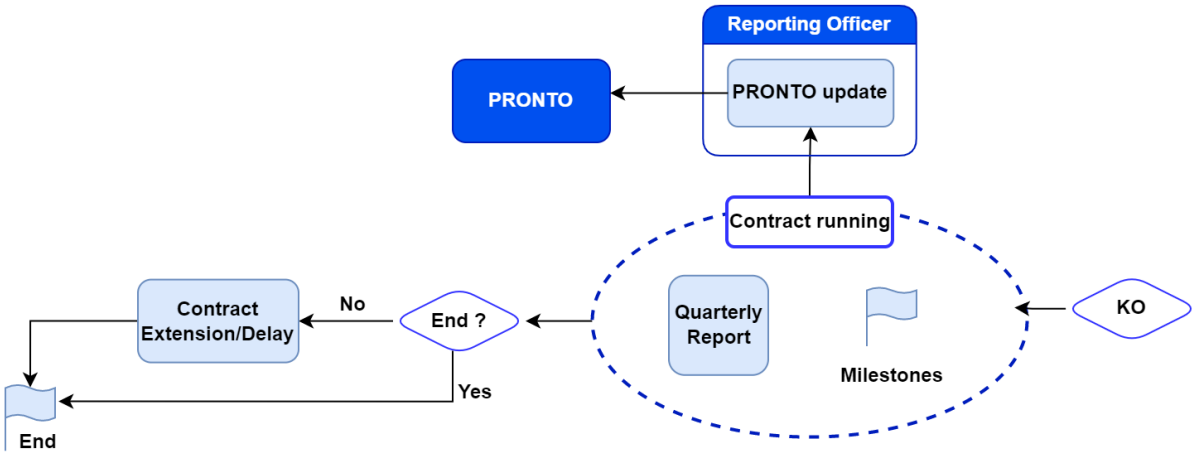


Figure 2.7: ExPeRT Monitoring and Control cycle

Along the development phase the Reporting Officer has three crucial tasks: upload all the procurement steps dates and contractors/sub-contractors budget share, report quarterly in PRONTO on the ongoing status of the activity and report the correct achievement (or not) of the milestones set in the contract.
Being all these steps in PRONTO, the tool itself is the only interface between ExPeRT and the ongoing status of the implementation. If the development proceeds nominally, no delay is accumulated and the milestones are reached within the contractual date, bringing the activity to the conclusion after the contract duration from the effective KO.
Unfortunately sometimes delays from the companies are accumulated and contract extensions/development delays occur, resulting in required updates on PRONTO. Overall, in the worst case the activity implementation can last way longer than planned.

Once the conclusion of the activity is reached, the status on PRONTO is set to *Completed*, and the TRL of the activity is successfully reached. [4]

2.3.4. Public outreach and R&D database

Once the end of the activity is reached the Technical Officer collects the lessons learnt and Technology Activity Summary/Template (TAS/TAT). From the completion of the contract a graphical representation of this last phase is shown in Fig.2.8.

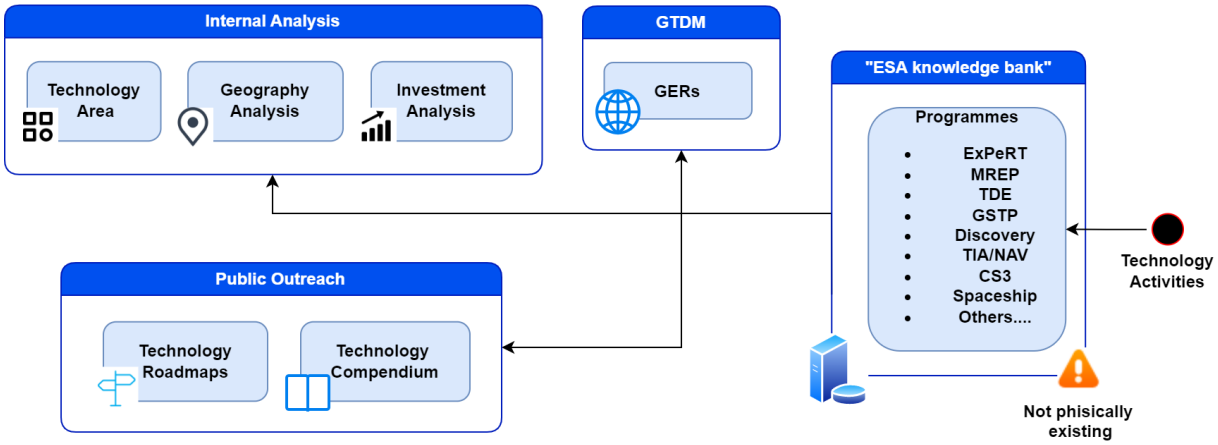


Figure 2.8: ExPeRT technology storage and public outreach

The cycle is now starting from two main inputs: the first one are the ExPeRT activities only (or in general all the activities under ExPeRT monitoring and control) because the process is monitored on PRONTO, which is an ExPeRT tool; the second input are the other programmes which deal with exploration (such as TDE, GSTP...), each of which presents its own reporting tools and database.
But at the purpose of exploration, when ExPeRT is publishing material regarding specific topics (the ISRU is taken as example in Chapter 4), also the technology activities are collected and included.

A seamless technology database, which is collecting all the activities belonging to different programmes is effectively missing, but efforts are ongoing at ESA to create such tool. In order to collect the information the different directorates have to be contacted and a list has to be "manually" generated with all the activities included.
Once the "list" is available, ExPeRT is yearly publishing a technology compendium, which embeds also other programmes, containing the technology activities relevant to exploration and relevant information for each of these (such as the technology area). Similarly,

[4] In some cases the activities can be cancelled, but in the 99% of the cases they are completed, even with accumulated delay.

roadmaps or technology capabilities assessments can be performed (see Chapter 4), and gantt charts representing technology roadmaps can be represented [7]. Another interesting analysis that can be performed is the mapping of ESA technologies with the Global Exploration Roadmap requirements (GERs), and the consequent Global Technology Development Map (GTDM) database update, but this part of TMT is beyond the scope of the thesis.

3 | Technology Management Tool for Exploration

Keep It Simple, Stupid

Kelly Johnson

This chapter represents the core of the thesis. The full process which lead to the implementation and development of ExPeRT Technology Management Tool (TMT) is explained, as well as the tool architecture, its connections and the reasons behind its current interfaces and capabilities.

TMT idea

The research question of the thesis starts from the ExPeRT Technology Flowchart.

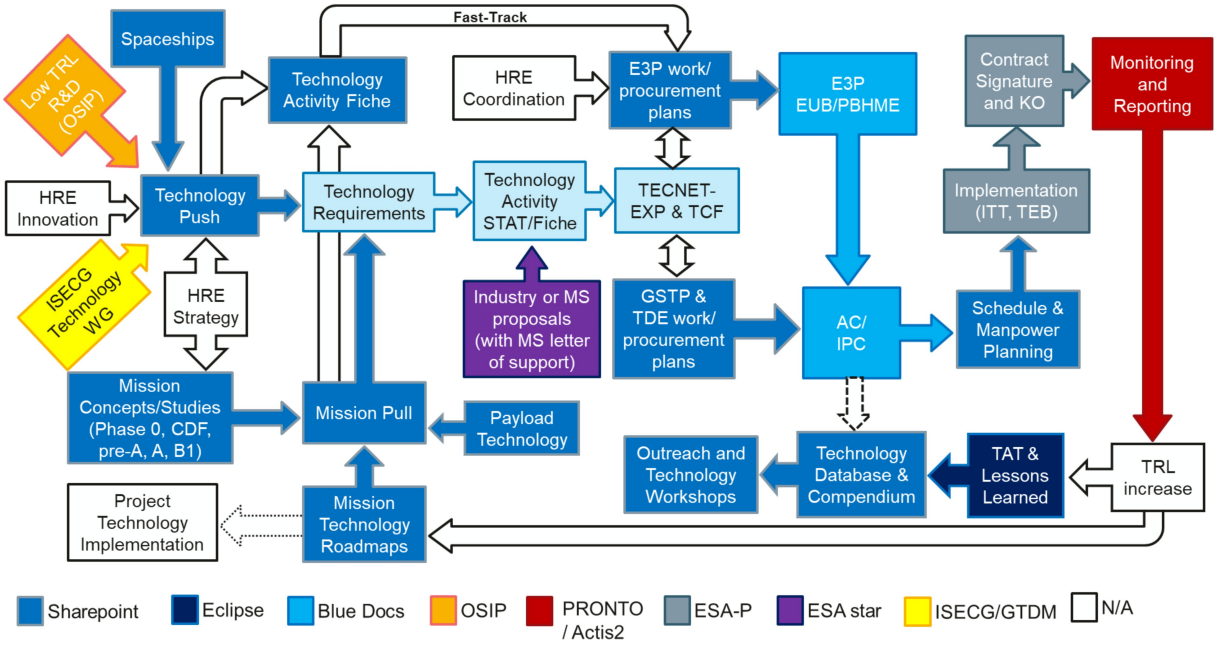


Figure 3.1: ExPeRT flowchart and current storing tools used

Its representation in Fig.3.1 shows the flowcharts together with the currently used tools and applications involved in the different steps. The complexity of the cycle is given from the large number of steps and entities involved that imply a continuous exchange of information, causing difficulties in monitoring and control operations in the whole life-cycle of activities. Considering the whole amount of activities that are approved each year, it's challenging to have a proper monitoring tool that allows to give a overview of the flow. A missing characteristic at this time is the possibility of having a general monitoring of the status of the activities under the team's domain, which can give the overall insight of the development status; the high number of activities makes it difficult to monitor them all, being each in different steps of the whole process. The idea is to import the entire project management process involved in the life-cycle within one platform, in use by ExPeRT, that is able to support the entire process: since the life-cycle can't be changed, the aim is to provide tools to support it. The platform would be ideally used not only as working tool, shared among the team and personnel involved, but also as a storage of information, so that all the data is available to the users, providing insight and overview of the whole development spectrum per each activity.

The objective of the thesis is therefore the one to demonstrate how a tool of such characteristics could beneficial to the project management life-cycle and providing support in the overall monitoring and tracking.

Constraints and Interfaces

In order to operate in the context of ExPeRT the already existing tools and methodologies have to be embedded and interfaced with the platform. There are three main constraints which the tool mock-up has to respect:

- PRONTO interface;
- the Microsoft Package;
- the integration within the ESA portal.

PRONTO Interface The core of the project management cycle is represented by PRONTO: in fact it is used by the whole team (and not only) as reporting tool for the activities. The first big constraint to respect if the interface with PRONTO, the tool in fact has to be connected to it somehow, and be capable of operating in its context without interfering with its usage.

Fiches, templates and Work Plans documents The European Space Agency signed a contract with Microsoft and is currently using the Microsoft Package 3.2 as default application for its daily operations.

Figure 3.2: Microsoft Package

This means that all the documents produced in the management framework and all the exchange of information correlated to it is using Microsoft Word (the activities are drafted via Word tables, same for the requirements and all the fiches connected), Microsoft Excel (Excel is used for programming and scheduling, as a database, and as a working tool given its accessibility in multiple parts of the flowchart), Microsoft Outlook (the exchange of information within the agency is working via email) and Microsoft Sharepoint (is the instrument used by the team for storing all the information and documents, providing an online collaborative environment).

Integration within the ESA portal The confidentiality of the data relative to ESA is the most important constraint. This implies that any tool or application in use by the ESA personnel which is sharing or storing any information correlated to ESA itself, starting with simply using its logo, has to be pre-approved. Not only, but also all the "working tools", therefore the applications which required to be shared, have to be embedded within the ESA portal, which in the case of ExPeRT means Sharepoint.
Being in fact Sharepoint the place where the team works and shares information it is crucial to maintain the working tools within the platform itself (PRONTO is the first example). Any platform developed in the context of the technology lifecycle has to be integrated and/or loaded in Sharepoint upon approval.

3.1. The low code approach applied to Excel

Given the constraints and the interfaces required the investigation starts analyzing the software needs. The main required technical features are listed hereafter:

- categorization of the informations: in terms of descriptions, number, codes and dates;

- possibility to attach and include documents in PDF and Word format;
- cross-links between the entries and parts of the tool;
- generation of gantts and milestones;
- generation of documents and deliverables in the framework of the Microsoft Package;
- filters for the applied categories;
- tagging and addressing tasks to ESA personnel;

For what concerns the expected performance, the tool is expected to increase the team independence, to be flexible and easily editable, but as the same time most importantly to be simple and reliable. An initial research and trade-off was run in order to select the most promising tool/software capable of demonstrating efficiently the potential of one single application embedding the all flowchart.

There are mainly two options identified since the beginning: traditional development and the low/no code logic. Low-code programming language, as it has a relatively simple syntax and does not require extensive knowledge of programming concepts to use effectively. Best low code no code platforms manage all the work done behind the scenes. Their users visually pick and connect reusable components representing certain phases (including the actual code) to construct the automated process. Instead of writing line-by-line scripts for each required function and capability, users may construct applications as if they were creating a flowchart. These platforms often include exploring, prototyping, testing, and deploying tools.

These are the three main tasks involved [48]:

1. data storage: largely rely on database tool (Excel for example);
2. automated workflows: pass automatically informations and do things automatically, so many databases tools have automatons as part of their software theirselves;
3. front end interface: build tool to allow people to access the tool directly.

In order to build no code the process to follow is:

1. map the process: so basically a logical architecture (see Fig.3.8);
2. build to scope: before I need to build my data structure and define it;
3. support phase: perpetual phase where the program is really updated and improved.

Given the initial purpose of the thesis, with the aim of supporting and demonstrating

how a tool can support the whole life-cycle, the low code option has been selected, being faster in the implementation and more flexible in the short term. The characteristic of using off-the-shelf products at ESA is that all of them require approval, purchase of the license and work from the IT organs to grant security and confidentiality during its nominal operation. These steps are conceived to be already part of the output of the research, in fact the eventual proposal of an external platform is addressed at the end of the thesis (see Section 5.2.2). At the easy purpose of showing the effectiveness of the tool, something immediate and rather simpler has to be implemented. Between the already available applications and tools, nothing is found to be project-management oriented, and answering the needs of the platform.

The idea is then to tackle the problem developing an Excel-based application, as simple as possible and widely known, already available and spread in ESA, which make use of embedded coding and macros to perform more complex operations automatically. This solution is also ensuring the support from the ESA developers which operate in the framework of Sharepoint, the possibility of starting with the immediate development, and the direct integration within ExPeRT Sharepoint under the vest of an Excel.

As it will be explained in Chapter 5 the solution based on Excel is not optimal, but it was considered beneficial and sufficient to support the TMT idea.

3.1.1. Visual Basic Application

Belonging to the Microsoft Package, Excel comes with Visual Basic Application (VBA) programming language [23]. VBA works with many applications and it is used to write programs to accomplish tasks automatically and/or change the application environment. TMT is developed under the vest of an excel, but embedding inside the VBA programming language not seen by the user. Some of the functionalities enabled by VBA are:

- automating documents;
- customizing an application's interface;
- performing calculations;
- adding features and making tools.

VBA is a visual programming environment. That is, you see how your program will look before you run it. Fig.3.3 shows how the Integrated Development Environment (IDE) looks like when it's open using Excel.

No matter which Office product and version of Windows you use, the editor has essentially

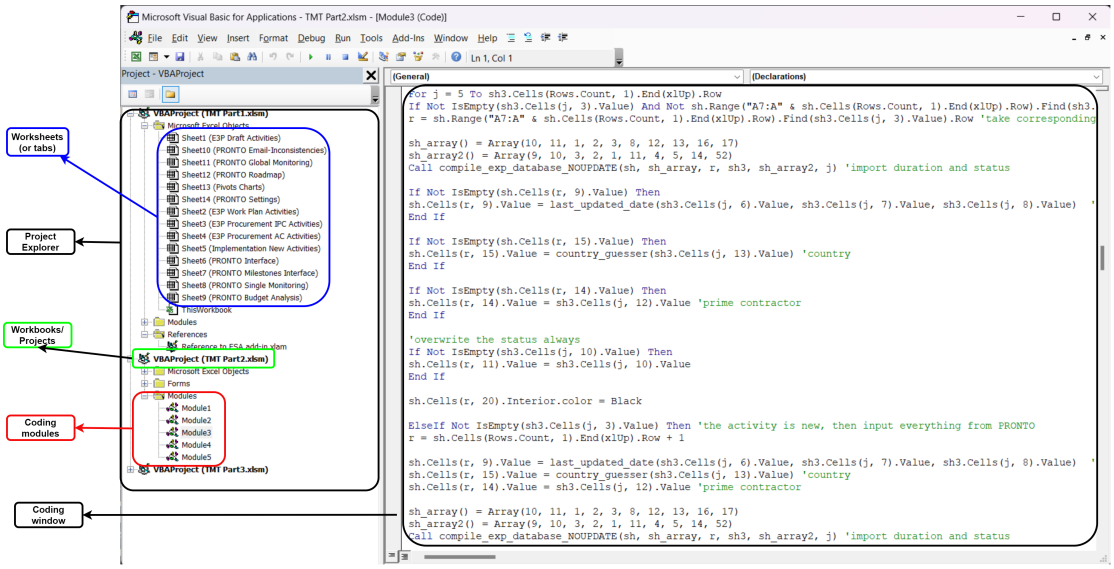


Figure 3.3: Excel Integrated Development Environment

the same appearance (and some small differences), the same menu items, and the same functionality. The IDE is a programming editor with special features that make it useful for writing instructions that the application should follow. These instructions are a set of steps. A project is an individual file used to hold the program, in the case of TMT it can be seen how 3 projects are present: TMT Part 1, TMT Part 2 and TMT Part 3. Inside each project a list of objects is present. In the case of TMT the objects are worksheets and workbooks, because it is developed in Excel. Apart from the Objects, also the Modules and Forms are present: the module is used to store the code of the application, while the Form contains user interface elements to interact with the user.

VBA coding architecture The screenshot of the TMT Part 1 project explorer is shown in the left column of Fig.3.3. It can be seen that the Excel sheets with the relative names are shown under the TMT Part 1 project, and in the coding window the macros are written inside the modules of the workbook. Both TMT Part 2 and TMT Part 3 present the same configuration. The coding logic and the specific subdivision inside the modules itself goes beyond the scope of the thesis, but Appendix **??** provides a high level overview.

Inside the modules Macros are contained. The macro is a set of actions that we can run as many times as required to perform a particular task. The macros represent the "functions" of the application, in fact each macro is running an automatic task on excel. By means of the macros automatic operation in Excel are run, and the flowchart steps/functions can be performed.

Button object In order to allow the user to run the macros without opening the IDE, Buttons Form controls are added to TMT, and each button is assigned to a macro (Fig.3.4).

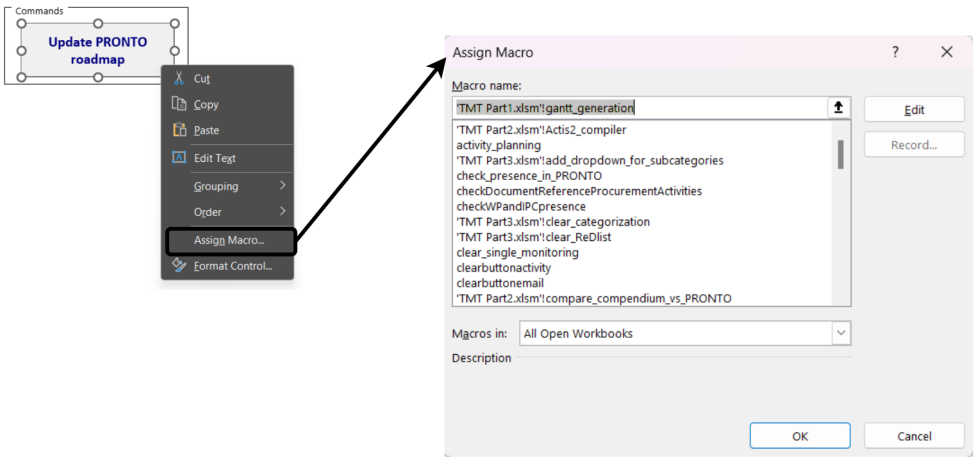


Figure 3.4: Macro assignment to Buttons

Therefore pressing the excel button the macros are run. In such a way excel is presented with his usual interface, simply equipped with buttons which allow the user to run macros.

3.1.2. Data exchange

The overall platform is based on exchange of data, exactly following the concept of the Technology Flowchart. The links are both internal and external to Excel, meaning that multiple Objects are interconnected.

Linkage

VBA allows to connect Excel with external sources via link/path and to access the content of the destination source. The command $wd.Documents.Open(sh.Cells(x, y).Value)$ is used to access the specific content of the $cell(x, y)$ and to open the the link associated, which should refer to an Excel. The whole platform works based on this logic, in fact in the cells are contained the link to the Objects (and the data of the tool itself). When an worksheet is connected to an external source, regardless the type of object (Word document or Excel), the path of the destination source has been included in the worksheets within a hideable row, allowing the user to draft the link if required (see Fig.3.5).

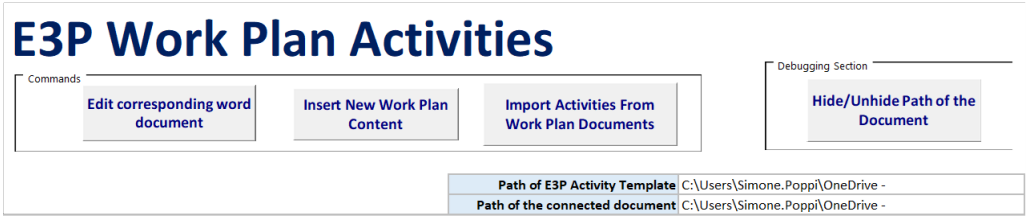


Figure 3.5: TMT link interface

From Word to Excel

The idea is to use Word and the associated documents as a repository of information under the format of Work Tables object, in such a way to respect the actual ESA templates, and then upload the data in Excel. Excel is used only as a list database, providing a graphical interface given its accessibility and flexibility in displaying the information.

The buttons in the Excel sheets allow to detect the Tables in the documents and translate the information from Word into Excel. The Fig.3.6 shows the data exchange between the fiche in the Word document and the screenshot of the TMT tab dedicated to drafting the E3P activities.

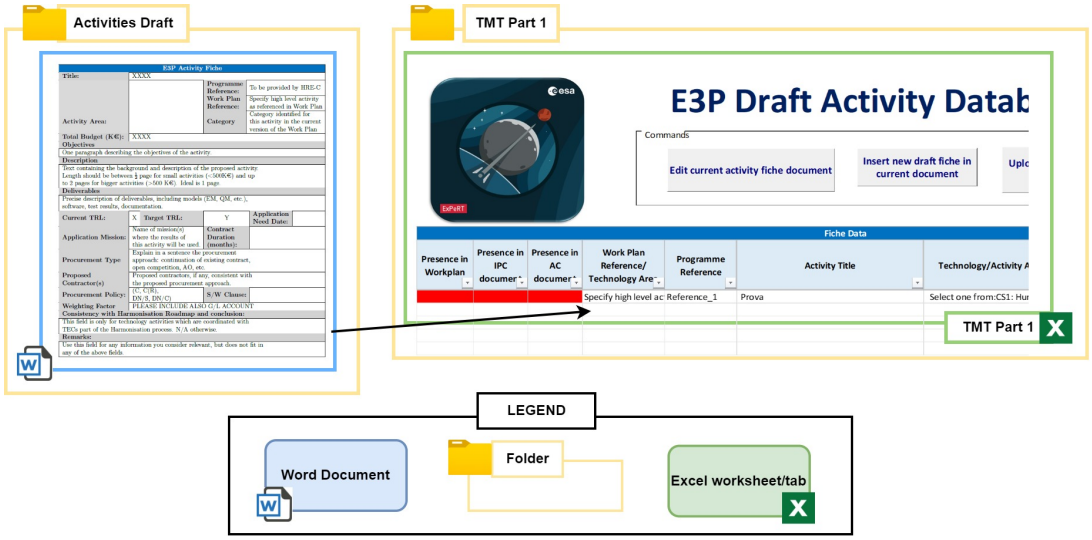


Figure 3.6: Word to Excel data exchange

When importing data from Word tables to Excel, the boarders are included in the import resulting in unknown character in the destination string in Excel: at this purpose custom functions have been created, in order to only keep the alphanumeric characters of the string.

Internal links The internal links between the tabs of the same Excel (the worksheets) are addressed defining the source and destination Excel sheets, and accessing the cell content with the $sh.Cells(x, y).Value$ command, the content of $cell(x, y)$ is read. At the purpose of the tool it is important to know the number of entries of the database in the Excel sheet, in fact all the information are stored in lists. The command $sh.Cells(Rows.Count, x).End(xlUp).Row$ represents the base in the working logic of the tool, in order to retrieve the last populated row in the column x, useful to determine the number of entries and loop inside the list.

3.2. TMT architecture

The overall TMT architecture and logic is addressed in this section. There are two "types" of architectures that have to be explained: the TMT "folder architecture", which represent how the folder and subfolders part of the tool are organized, and the TMT "logical architecture", representing the transposition of the logical steps of the technology process lifecycle inside the "folder architecture".

3.2.1. TMT folder architecture

The Technology Management Tool is composed of several excel workbooks and connected documents.
The whole architecture is contained within one main folder called TMT; see the left-hand side of Fig.3.7. The whole TMT folder is uploaded to the ExPeRT Sharepoint, therefore all the application is included in it. This keeps the information under ExPeRT Sharepoint, representing the "unique source of truth" following the MBSE concept, and most importantly allowing the team collaboration on the same platform.

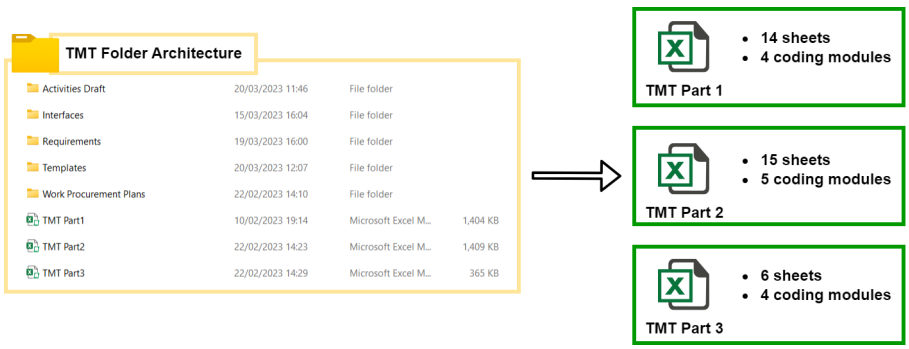


Figure 3.7: TMT folder architecture

The initial idea was to develop the overall platform with one single Excel workbook

(namely TMT Excel, instead of 3 different workbooks), but during the development the dimension of the file and the amount of processes in background during its usage was preventing the tool to be operationally efficient. The final design is therefore the breakdown of the TMT content into 3 excel workbooks linked to each other: TMT Part 1, TMT Part 2 and TMT Part 3. Accordingly to Fig.3.7 the workbooks embed a number of userforms and modules which in turn contain the macros. Approximately the whole TMT contains ∼60 macros.

3.2.2. TMT logical architecture

The TMT logical architecture is representing the Technology Flowchart steps and cycles under the vest of the folder architecture, therefore the transposition of the whole chart has been carried out in the TMT folder. The logical architecture of the flowchart connecting to it is presented in Fig.3.8. It can be seen that the three main parts composing TMT are interconnected, contributing to the generation of the flowchart translated into Excel. Each of the TMT Parts is explained opportunely, as well as the interconnections and the step-to-step working logic of the tool.

3.3. TMT Part 1: from procurement to implementation

The zoom on the logical architecture of TMT Part 1 and its interconnections is shown in Fig.3.9. The architecture can be further decomposed into 4 main steps, highlighted with the red dashed line in the figure, representing the Technology Flowchart phases:

1. ExPeRT Data upload;
2. schedule and manpower planning;
3. PRONTO connection
4. data analysis, monitoring and control.

It is important to highlight that being the procurement and implementation steps internal to ESA, this section is not presenting any practical data or results due to ESA privacy policies; the focus is given to the platform functionalities and processes.

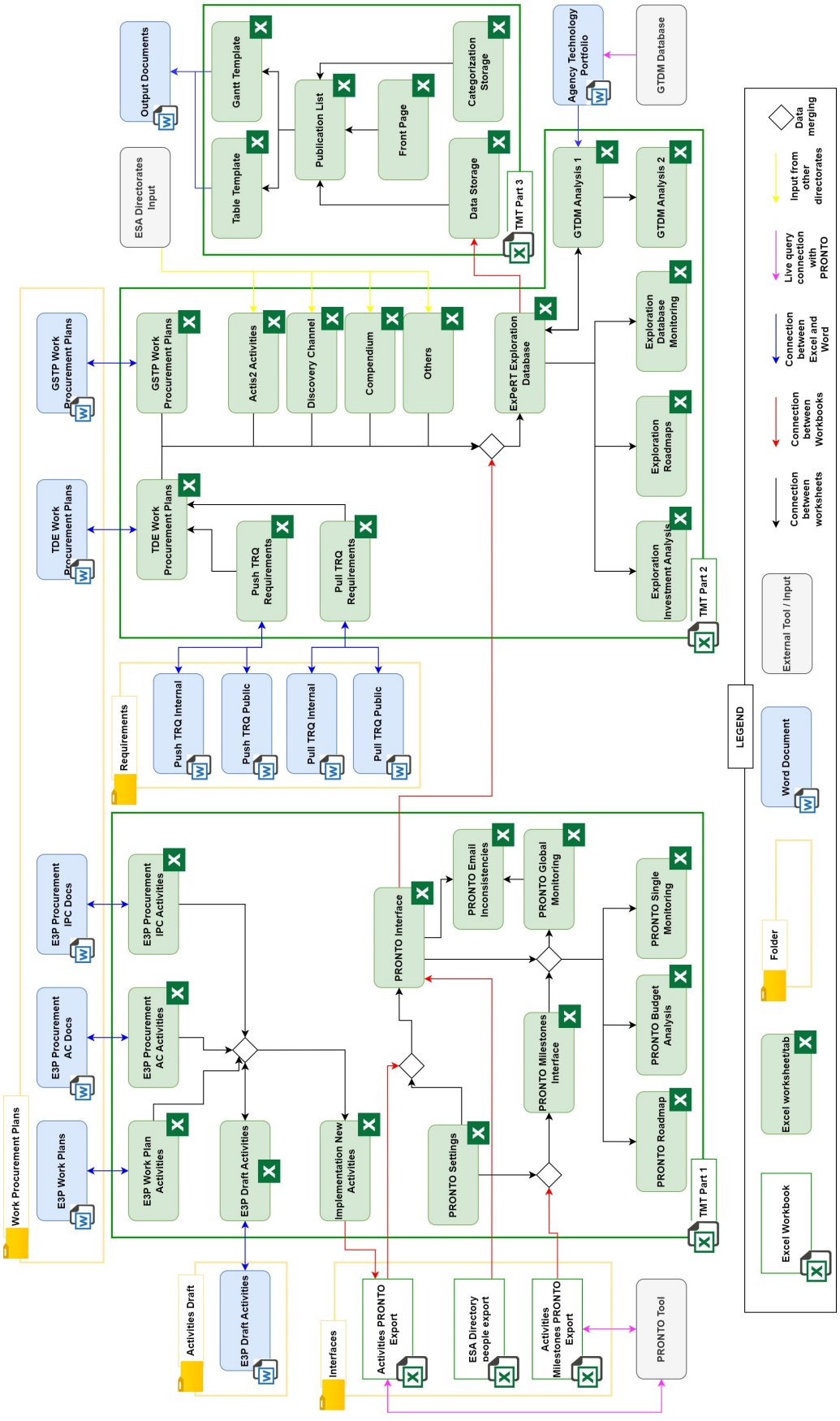


Figure 3.8: TMT Logical Architecture

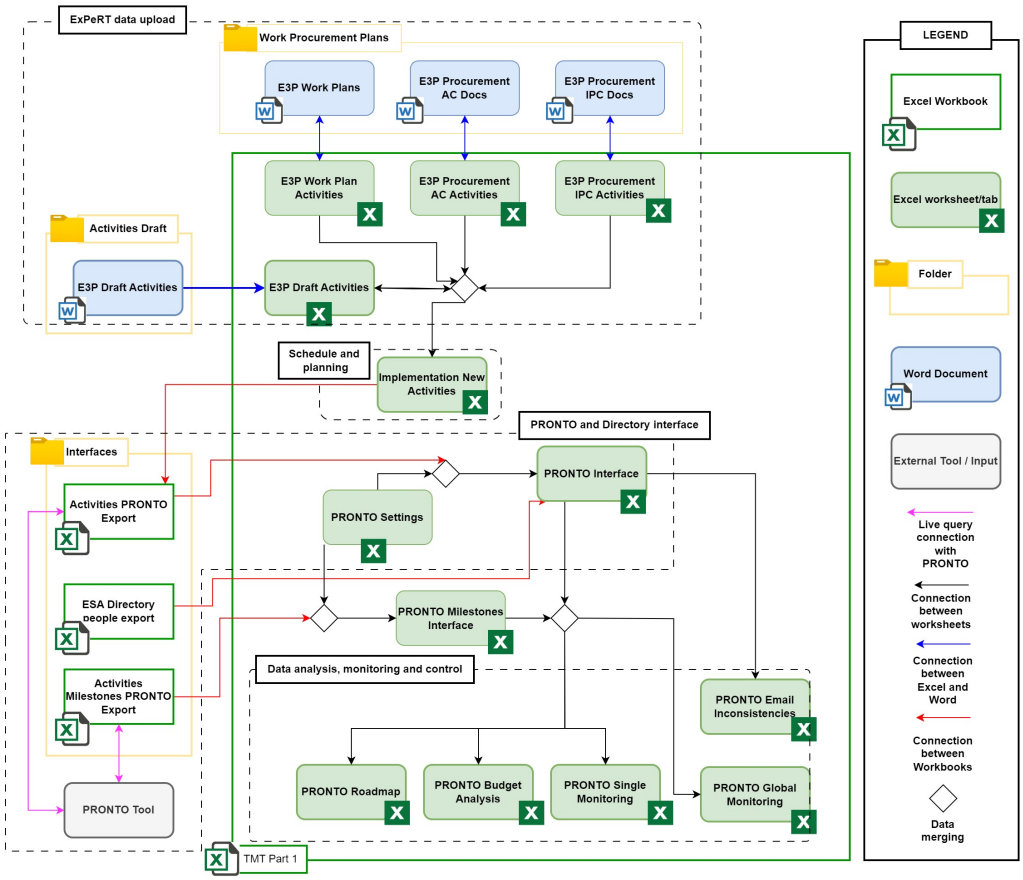


Figure 3.9: TMT Part 1 Logical Architecture

3.3.1. ExPeRT Data upload

Although the Technology flowchart starts with the definition of the requirements, being the platform in use by ExPeRT and the requirements only linked to D/TEC activities, the direct implementation of ExPeRT starts with the definition of the activity fiches.

From the top left of Fig.3.9, the whole cycle starts with the upload to TMT of the fiches contents and Work Plans. Appropriate sheets and commands are included in order to facilitate this operation.

E3P Draft activity

In the specific case of the E3P activities, the *E3P Draft activity* sheet is allowing the user to include a new activity in the Word document by adding a new empty template, drafting the template with the activity data, and upload the new activity in Excel. Every time ExPeRT has to introduce a new activity the sheet is used at the purpose, storing all the new fiches in the connected Word document. The command bar together with the

sheet view is shown in Fig.3.10.

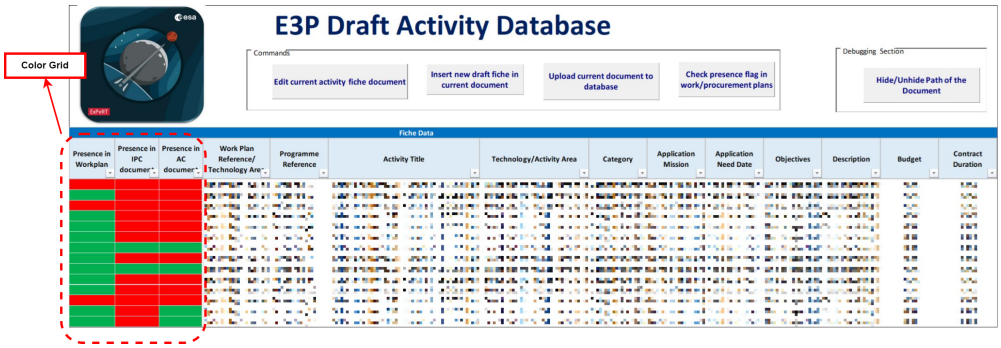


Figure 3.10: Screenshot of the *E3P Draft activity* tab

Is is important to make some considerations on the *Check presence flag in work/procurement plans* button, connected to color grid in the tab.

As explained in Chapter 2.3, the activity procurement cycle start with the insertion of the activity fiche inside a Work Plan, then successive insertion in the AC Procurement Plan, and in the end, part of the activities reach the IPC Procurement level. Each of the flags is associated with one of these steps, so once the activity reached one of these levels, the flag turns green being the activity embedded in the corresponding Excel sheet (one Excel tab and connected document has been created for each of the steps). In this way the actual status of an activity can be tracked, and in any moment the user knows at which stage of the procurement each activity is.

E3P Work/Procurement Plans

The same import logic is applied to the tabs dedicated to the Work and Procurement Plans: *E3P Work Plans*, *E3P Procurement AC Activities*, *E3P Procurement IPC Activities*. Despite the graphical interface is substantially the same of the *E3P Draft activity*, the one main difference is that the Work and Procurement Plans contain more than one activity each. This means that the same Work Plan can be attributed to multiple fiches. At this purpose the Excel button *Insert New Work Plan Content* is asking to the user the number of activity to insert (see Fig.3.11), and from the *Templates* folder the E3P fiches are properly copied and pasted in the destination document.

Once the same activity reference is both present in these three tabs, and in the *E3P Draft activity* tab, the flags of *E3P Draft activity* turn all green, meaning that the activity has reached IPC approval and can then undergo the schedule and manpower planning cycle.

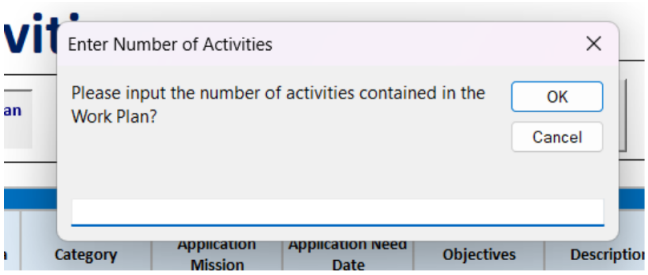


Figure 3.11: Number of activities input in the E3P Work Plan

3.3.2. Schedule and manpower planning

Once the activity has reached IPC level it is ready to be submitted to the implementation cycle. There are 3 main steps involved in the schedule and manpower planning for the *Implementation New Activities* tab:

1. procurement step scheduling;
2. assignment of manpower;
3. upload to PRONTO.

The *Implementation New Activities* command window is show in Fig.3.12.

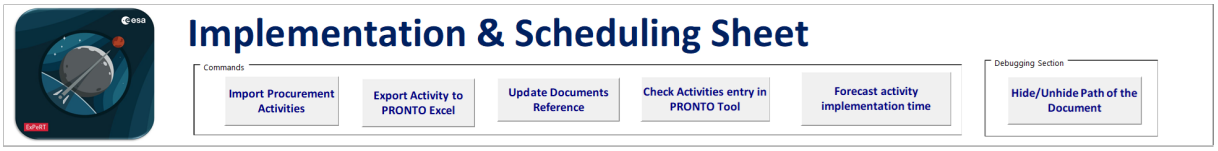


Figure 3.12: *Implementation New Activities* command window

Each of the buttons is associated to one of the automation required for the scheduling tasks. The *Import Procurement Activities* button allows to import in the tab the activities data which already reached the implementation level (therefore the activities whose flags are green in the *E3P Draft Activity Fiches* colour grid).

Implementation step scheduling

The implementation steps (introduced in Fig.2.4) start with the formulation of the draft SoW. Once the RO knows this information, the draft date (planned one) is fetched in the Excel column. The *Forecast activity implementation* button is then automatically calculating the required planned time for the overall implementation cycle, providing a rough idea of the KO date expected for the activity and date associated to each step. For the scope of the thesis, Tab.3.1 shows the assumed time required for each implementation

step. [1]

Implementation steps	Notional timeline (weeks)
SoW formulation	TO
Pre-TEB	TO + 4
ITT/RFQ issue	TO + 10
ITT/RFQ close	TO + 18
TEB	TO + 21
Negotiation	TO + 26
KO	**TO + 32**

Table 3.1: Implementation notional timeline

The timeline shown in 3.1 is assuming an overall 6 months time require for the implementation cycle. Actually what happens is that the implementation time is depending on the procurement cycle, therefore based on the procurement type the implementation time can mainly vary between: 32 weeks for the C-type of procurement or half of it (16 weeks) for the Direct Negotiation type.
Following this logic, as TMT is embedding the procurement type, once the RO inputs the draft SoW date the tool is automatically calculating the expected KO date (see Fig.3.13).

Manpower Planning						Contract Implementation Forecast							
Technical Officer	Reporting Officer	Contract Officer	Project Controller	ExPeRT Interface	Chairperson (if TDE)	Draft SoW Date	Pre-TEB	ITT/RFQ issue	ITT/RFQ close	TEB	Negotiation	KO	Forecast End of Activity
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	01/10/2023	29/10/2023	10/12/2023	04/02/2024	25/02/2024	31/03/2024	12/05/2024	12/05/2025

Figure 3.13: Manpower and planning interface

Assignment of manpower

ExPeRT is also responsible of planning the manpower involved in each activity; a small section of the tab is therefore dedicated to this task; the user can directly draft the Excel tab in the given space in Fig.3.13.

3.3.3. PRONTO and Directory interface

Once all the data have been input and the implementation sheet has been populated, the activity is now ready to be uploaded to PRONTO, allowing the assigned personnel to track its development and actual procurement steps by operating in the PRONTO context.

[1] This is not corresponding to the real time required by the step or in use by ESA, it is just a fictitious time reasonably assumed at the purpose of the thesis development.

Upload to PRONTO

The upload to PRONTO was before operated by the Sharepoint developers who were receiving the activities list, and were uploading manually the activities to PRONTO. Having now the list of the activities which have already reached the IPC approval, it is considered crucial for ExPeRT to gain independence in the upload to PRONTO: in fact if the ExPeRT team would be autonomous in the upload operation, the interface with the Sharepoint personnel could be discarded. The autonomy in the upload operation has been reached by introducing the *Export Activity to PRONTO Excel* button (and connected macro). In order to understand how the upload is actually working the interfaces have to be introduced.

PRONTO connection

The need is to include the capability of having an instrument which allow the user to load activities from an Excel worksheet to the protected HTML platform, and vice-versa, therefore downloading the PRONTO content in an Excel format to merge the data with TMT. An excel-based live query has been created at this purpose, representing the same content of PRONTO but in Excel environment. Two different workbooks are used: the *Activities PRONTO Export* and the *Activities Milestones PRONTO Export*. The two workbooks are then live-connected to PRONTO: this means that any change in PRONTO would change the Excel content and vice-versa. In order to achieve the upload capability (therefore by drafting the Excel also the PRONTO content is changed) it is required to install in excel the add on shown in Fig.3.14.

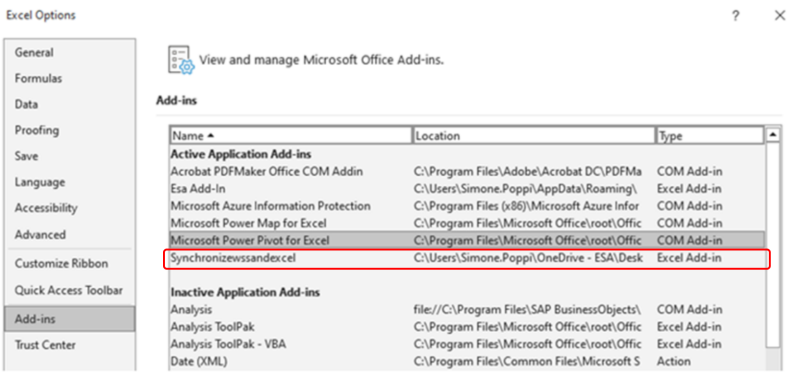


Figure 3.14: Excel add-in for PRONTO live query

In this way the PRONTO content both in terms of activity data and milestones is generated. The overall scheme for the PRONTO interface is introduced in Fig.3.15.

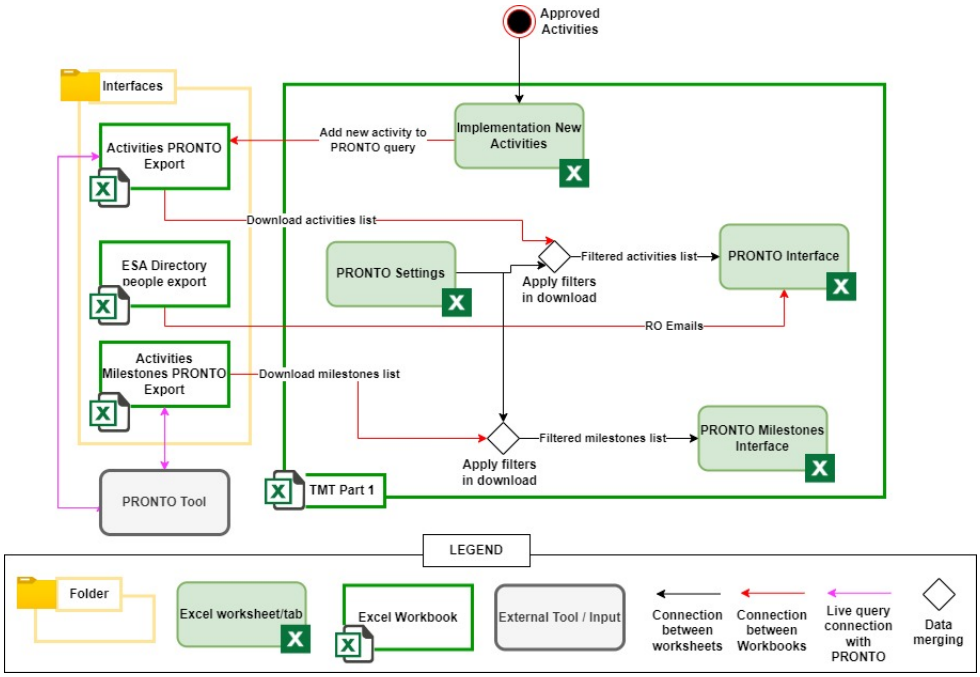


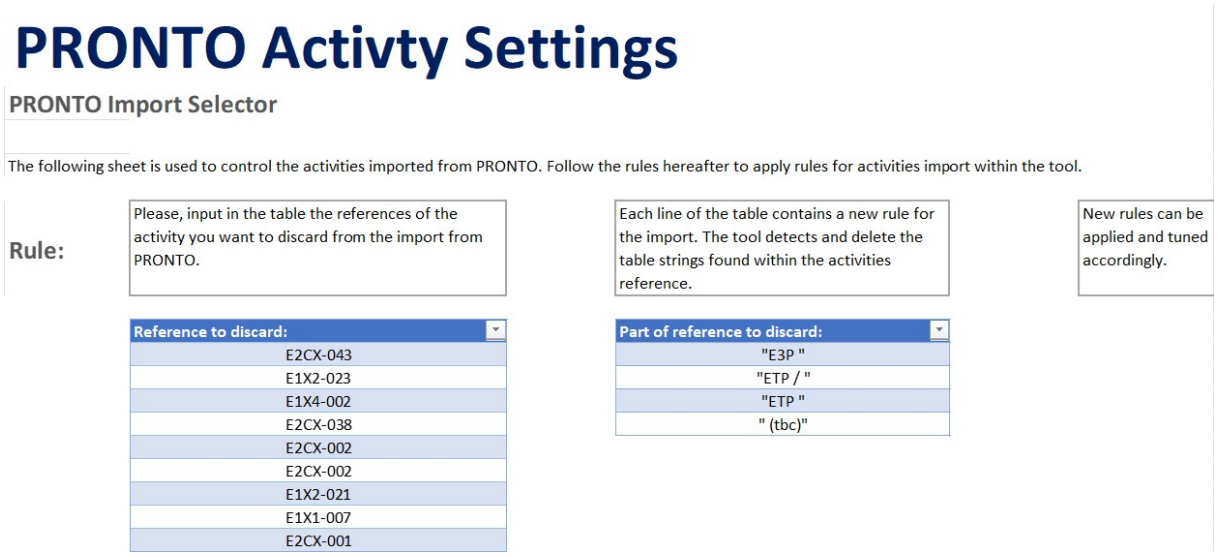
Figure 3.15: PRONTO interface with TMT

PRONTO Content

The PRONTO content is composed by activities which were previously sent by ExPeRT to the Sharepoint developers, responsible for the upload. In this framework there was no discrimination between the types of activities which were uploaded because the developers are not part of ExPeRT. Due to the lack of control in the upload phase, PRONTO is not only including technology activities, but also mission studies and parallel contracts. [2] The tool instead is conceived as a tool working in the framework of the technology activities only. It is therefore required to filter and discard the unwanted activities in download from the full list.

In order to allow any user to apply filters without coding, the *PRONTO setting* tab 3.16 has been introduced: the idea is to provide the user with a editable list containing the references of the activities (which as it was explained, are unique for each of them). The same logic can be applied in the operation of editing part of the reference.

[2]The parallel contracts are technology activities or mission studies which actually are the same activity, with the same reference, but assigned to two competing contractors, therefore representing 2 different entries, but with same reference.



PRONTO Activty Settings

PRONTO Import Selector

The following sheet is used to control the activities imported from PRONTO. Follow the rules hereafter to apply rules for activities import within the tool.

Rule:

Please, input in the table the references of the activity you want to discard from the import from PRONTO.

Each line of the table contains a new rule for the import. The tool detects and delete the table strings found within the activities reference.

New rules can be applied and tuned accordingly.

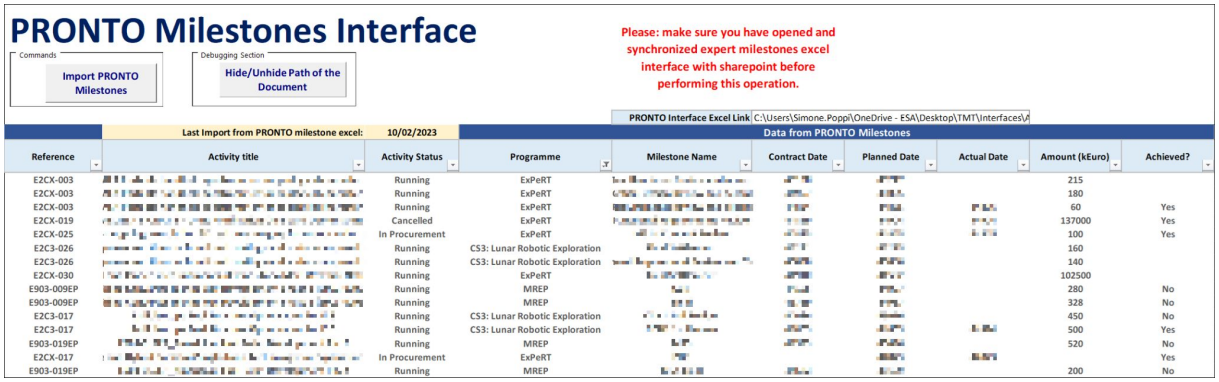
Reference to discard:
E2CX-043
E1X2-023
E1X4-002
E2CX-038
E2CX-002
E2CX-002
E1X2-021
E1X1-007
E2CX-001

Part of reference to discard:
"E3P "
"ETP / "
"ETP "
" (tbc)"

Figure 3.16: *PRONTO Settings* interface

PRONTO download

Connecting then *PRONTO setting* to both the activities list and milestones, the same PRONTO content, but filtered and including only the technology activities, is downloaded in TMT in *PRONTO interface* and *PRONTO Milestones interface* tabs. Fig.3.17 is showing the screenshot of *PRONTO Milestones interface*, and *PRONTO interface* follows the same logic.



PRONTO Milestones Interface

Commands — Import PRONTO Milestones

Debugging Section — Hide/Unhide Path of the Document

Please: make sure you have opened and synchronized expert milestones excel interface with sharepoint before performing this operation.

PRONTO Interface Excel Link C:\Users\Simone.Poppi\OneDrive - ESA\Desktop\TMT\Interfaces\

Last Import from PRONTO milestone excel: 10/02/2023

Data from PRONTO Milestones

Reference	Activity title	Activity Status	Programme	Milestone Name	Contract Date	Planned Date	Actual Date	Amount (kEuro)	Achieved?
E2CX-003		Running	ExPeRT					215	
E2CX-003		Running	ExPeRT					180	
E2CX-003		Running	ExPeRT					60	Yes
E2CX-019		Cancelled	ExPeRT					137000	Yes
E2CX-025		In Procurement	ExPeRT					100	Yes
E2C3-026		Running	CS3: Lunar Robotic Exploration					160	
E2C3-026		Running	CS3: Lunar Robotic Exploration					140	
E2CX-030		Running	ExPeRT					102500	
E903-009EP		Running	MREP					280	No
E903-009EP		Running	MREP					328	No
E2C3-017		Running	CS3: Lunar Robotic Exploration					450	No
E2C3-017		Running	CS3: Lunar Robotic Exploration					500	Yes
E903-019EP		Running	MREP					520	No
E2CX-017		In Procurement	ExPeRT						Yes
E903-019EP		Running	MREP					200	No

Figure 3.17: PRONTO Settings

It can be seen for the screenshot that the activities are listed together with the programme to which they belong, the contract, planned and actual date of the milestone, the relative budget and the achievement status. These are in fact the data which pose the basis for further analysis

Activities ID and programme The activity programme it is not present in the fiche. During the import in TMT, the activity programme is recognized based on the reference. In such a way it is possible to automatically recognize and allocate the corresponding program to the activities. Each programme is following different logic and rules to assign the reference, and although each activity presents his own reference, there are parts of the reference which are repeated; it's from the standardization of the format of the acronyms that is possible to distinguish between different technology programmes, in fact each programme uses its own pattern for the assignation of the reference. At the purpose of the thesis it's important to highlight the different patterns used for the existing programmes listed in Section 2.2.1. The patterns and corresponding programme are presented in Tab.3.2, respecting the *regex* rule implemented in VBA (Appendix A displays the used algorithm).

Programme Reference	Programme
E1..-	ExPeRT Period 1
E2..-	ExPeRT Period 2
E9..-	MREP
E.C3-	CS3: Lunar Robotic Exploration
G...-	GSTP
T...-	TDE

Table 3.2: Programme reference *regex* patterns

ESA directory

The download operation of the activity content is also including all the personnel associated with each activity. The Reporting Officer of each activity is the figure responsible of reporting for the activities, so in case of inconsistencies or data missing this is the person who has to be contacted.

Unfortunately the download query is still not including the emails of the RO. At this purpose a different strategy is used.
The full ESA directory is downloaded (*ESA Directory people export*): this is a list which is containing names and contacts of all the people working in/per ESA. [3] Applying a name-matching algorithm to the name of the RO imported in TMT, the corresponding email is retrieved from the *ESA Directory* workbook, in such a way to include the emails and contacts in TMT.

[3]ESA staff and contractors mainly.

3.3.4. Data analysis, monitoring and control

TMT is now embedding the full capability to interface with PRONTO, together with all its data, and more, in fact the full procurement cycle from the E3P activity draft is present. Given the amounts of contracts and activities both ongoing and closed, it is useful to perform some analysis of the present data in the platform, as well as monitoring and control of the ongoing contracts, and the one who are under procurement or in preparation. The actual database generated in TMT Part 1 can be now analyzed and used.

Once the activities are loaded to PRONTO, in the implementation steps of each activity there are a set of possible status downloaded from the tool:

- In Preparation: the activity has been approved;
- In Procurement: the activity is undergoing the implementation cycle;
- Running: KO reached and activiy running;
- Completed;
- Cancelled: rarely can happen.

PRONTO Global Monitoring

Firstly, analyzing the full list of activities, the dashboard in Fig.3.18 is generated. Importing in fact the activities based on the programme and the implementation status the overall statistic tables can be populated as to provide ExPeRT with a complete overview of the amount of activities per status.

Basically the dashboard is used to know which is the percentage of the activities which are ongoing, undergoing procurement or closed, broken down per single program. The Excel pivot charts are used to give a filtered overview based on the status and/or programme in interest.

Delays and Inconsistencies The bottom part of the dashboard is introducing the activity list for which the delays and the inconsistencies have been detected from the overall implementation steps. This operation was before performed singularly per activity, therefore TMT represents the first attempt of its automation. According to the given rules (that can be completely tuned and changed) the platform is able to detect and rise flags on certain activities.

For what concerns the delays, these are mainly of two kinds:

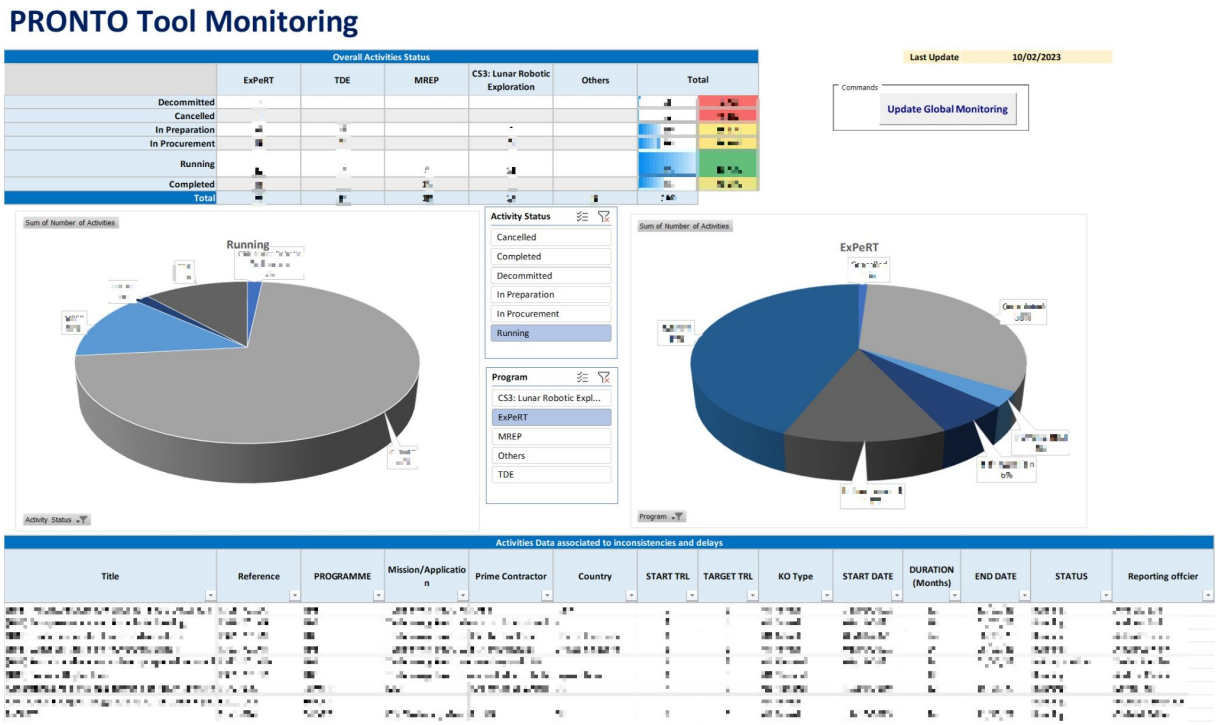


Figure 3.18: *PRONTO Global Monitoring* screenshot

1. the actual delays, which represent the activities whose status is set to Running and closing date (calculated based on reported KO and duration) was prior to today's date;

2. the expected delay, which is the delay which occurs when there is a set milestone date that is after the calculated closing date of the activity (so it's in the future).

Tracking these conditions is therefore immediate to give a global overview to ExPeRT on the number of activities which are ongoing with delay and which are the amount of delays which have been accumulated. Often the expected delays can be caused by contract extensions, or simply RO officers who forgot to update some involved dates.

Regarding the inconsistency, TMT is tuned to monitor and rise flags on the chosen "rules" in the implementation which have not been respected. The chosen monitored inconsistencies are:

1. KO Date and/or duration missing;

2. activity running with a not achieved milestone in the past;

3. starting date in the past: the activity status is still under procurement but the KO date was in the past;

4. not achieved milestone in the past with activity in procurement/preparation;
5. activity running with KO date in the future.

It is important to remark that the inconsistencies can be completely tuned, in fact these are the main one which have been detected and chosen to be tracked and flagged.

Inconsistencies and Delays				
Flags	Associated Milestone (If any)	Milestone Date	Actual Delay (Month)	Expected Delay from milestones (Month)
Actual delay detected			1	
Expected delay calculated from milestone dat	[illegible]	19/06/2023		1
Expected delay calculated from milestone dat	[illegible]	14/03/2024		6
Expected delay calculated from milestone dat	[illegible]	10/11/2023		2
The activity starting date was in the past				
KO Date and/or duration is missing				
Actual delay detected			30	
KO Date and/or duration is missing				
Actual delay detected			16	
The activity starting date was in the past				

Figure 3.19: *PRONTO Global Monitoring* inconsistencies and delay flags

The table generated from the list of activities shown in Fig.3.19 is providing the flags and the associated milestones per each activity. Is therefore immediate to have filter the activities per category to perform quick research on activities data or personnel involved. The severity of the delays is also reported applying a simple excel color gradient, this allows to give an immediate view of the most severe delays.

PRONTO Roadmap

In terms of global view of the PRONTO content, another interesting analysis and task involved in the project management life-cycle is to track the implementation status in time. From *PRONTO Interface* the list is retrieved together with the K0 date adn the associated milestone dates. The gantt is used to generate a roadmap which includes all the activities regardless of the status and programme, therefore representing the screenshot in time of the activities development cycle in PRONTO. From the duration and the KO date the End date is automatically calculated. One consideration has to be made for what concerns the KO date; all the dates can have 3 different states (see Fig.2.7): planned, contract and actual. Not all the dates are always reported by the RO, in fact most of the time only one of these is reported. At the purpose of generating the roadmap the *KO type* column is used to retrieve the last update KO date and actually have a KO date to be used for the roadmap.

The roadmap is both including the development timeline and the the milestones for each activity, useful to provide the overview of the actual development associated. An ad

hoc interface and associated script has been implemented to generate roadmaps with the following features:

- bar colors per programme: each programme is associated to a different color;
- milestones: the milestones have been represented with a black dot in the diagram providing a graphical view for each of the activities;
- current and forecasted delays represented graphically by means of red flags.

Fig.3.20 is representing the interface provided by TMT in the gantt environment of the activities development line and associated milestones.

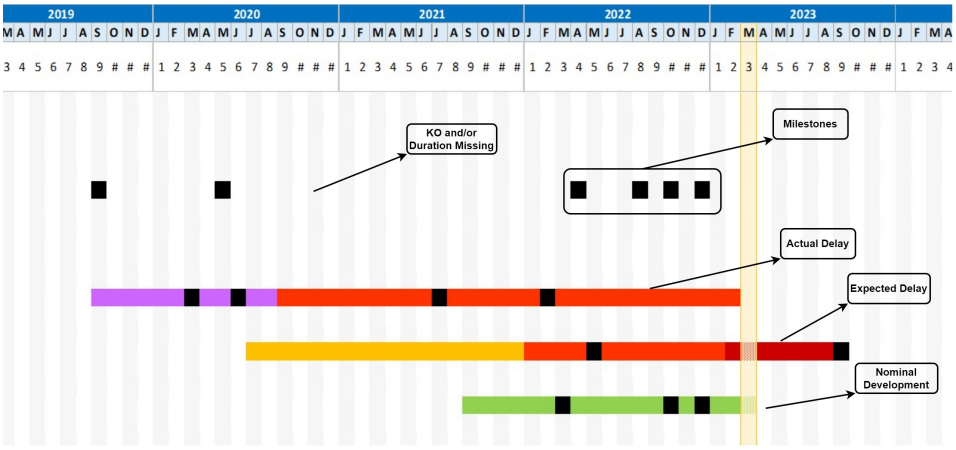


Figure 3.20: *PRONTO Roadmaps* zoom

Displaying the PRONTO content for the first time by means of a gantt chart the implementation status is graphically provided to ExPeRT. From the gantt it's immediate to notice which are the activities whose data are missing and that have inconsistencies: if the color bar is not present in the chart it means that either the KO or the duration is not present, and following the same logic, when the black dots for the milestones are outside the development line inconsistency are fetected and flags are raised (Fig.3.20).

PRONTO Budget Analysis

In the European space sector ESA acts as a client, commissioning the contracts to the companies with the available budget. In this framework ExPeRT is monitoring the cash-flow invested under several aspects. The budget present in the fiche for each activity is the budget which is assigned to the prime contractor who wins the contract. The sub-contractors are then engaged by the prime in order to split the effort and expertise in the development of each activity.

It is important for ExPeRT to analyze where the investment have been placed and which are the countries/companies winning the contracts. The table of the *PRONTO Budget Analysis* tab 3.21 is representing an example of how the excel tab is used, displaying the budgets breakdown per country and contractor types. It is important to remark that the data shown are not the real one of ExPeRT, in fact this is only a simulation used as graphical purposes.

ExPeRT Geography Investment Analysis

Commands: Update Investment Analysis

Last Update: 22/03/2023

Investment Analysis per Country

ExPeRT Investment analysis per Country		Prime Contractor				Sub Contractor				TOTAL			
Country	Acronym	N of Activities		Budget		N of Activities		Budget		N of Activities		Budget	
Austria	AT		0.0%		0.0%		0.0%		0.0%	0	0.0%	0	0.0%
Belgium	BE	2	8.0%	699.986	4.7%	1	6.3%	1000	20.5%	3	7.3%	1699.986	8.3%
Canada	CA		0.0%		0.0%		100.0%	134	2.7%	0	0.0%	134	0.7%
Czech Republic	CZ		0.0%		0.0%		100.0%	39.94	0.8%	0	0.0%	39.94	0.2%
Denmark	DK		0.0%		0.0%		0.0%		0.0%	0	0.0%	0	0.0%
United Kingdom	UK	2	8.0%	2449.49	16.5%	1	200.0%	156.2	3.2%	3	7.3%	2605.69	12.8%
Estonia	EE		0.0%		0.0%		0.0%		0.0%	0	0.0%	0	0.0%
Finland	FI		0.0%		0.0%		0.0%		13.9%	0	0.0%	680	3.3%
France	FR	3	12.0%	1777	11.9%	3	100.0%	680	13.9%	6	14.6%	2457	12.0%
Germany	DE	3	12.0%	1287.937	8.7%	4	400.0%	936.664	19.2%	7	17.1%	2224.601	10.9%
Greece	GR		0.0%		0.0%		0.0%		0.0%	0	0.0%	0	0.0%
Hungary	HU	1	4.0%	1	0.0%		0.0%		0.0%	1	2.4%	1	0.0%
Ireland	IE		0.0%		0.0%		0.0%		0.0%	0	0.0%	0	0.0%
Italy	IT	6	24.0%	4104.3	27.6%	3	400.0%	400	8.2%	9	22.0%	4504.3	22.0%
Luxembourg	LU	1	4.0%	200	1.3%	1	6.3%	350	7.2%	2	4.9%	550	2.7%
Netherlands	NL		0.0%		0.0%		0.0%		0.0%	0	0.0%	0	0.0%
Norway	NO	5	20.0%	2371.103	15.9%		100.0%	350	7.2%	5	12.2%	2721.103	13.3%
Poland	PL		0.0%		0.0%		0.0%		0.0%	0	0.0%	0	0.0%
Portugal	PT		0.0%		0.0%		100.0%	320	6.6%	0	0.0%	320	1.6%
Romania	RO		0.0%		0.0%		0.0%		0.0%	0	0.0%	0	0.0%
Sweden	SE	1	4.0%	272	1.8%	1	6.3%	248	5.1%	2	4.9%	520	2.5%
Slovenia	SI		0.0%		0.0%		0.0%		0.0%	0	0.0%	0	0.0%
Spain	ES		0.0%		0.0%		100.0%		0.0%	0	0.0%	0	0.0%
Switzerland	CH	1	4.0%	1710	11.5%	2	300.0%	265	5.4%	3	7.3%	1975	9.7%
	TOTAL	25		14872.816		16		4879.804		41		20432.62	

Figure 3.21: Investment breakdown example

The sum of the prime and sub-contractors budget should be equal to the overall budget allocated for the corresponding activities. Currently PRONTO is only providing the capability of including 1 prime contractor and 2 sub-contractors, while the contracts can include also more sub-contractors (sometimes up to 5 can be present). Including only 2 subs results in a breakdown of the budget which is not representative of the whole budget assigned to the activity. For this reason the proposal of updating PRONTO with the capability of including more sub-contractors has been made, and it would useful to obtain the full match between the contract budget and contractors budget, providing the reliability of the geography investment analysis.

The countries are recognized based on the ESA member states and standard acronyms of the agency of Tab.3.3.

PRONTO Email-Inconsistencies

The three tabs which have just been introduced are used to monitor the overall activities development.

ESA member states			
Austria	**AT**	Italy	**IT**
Belgium	**BE**	Luxembourg	**LU**
Canada	**CA**	Netherlands	**NL**
Czech Republic	**CZ**	Norway	**NO**
Denmark	**DK**	Poland	**PL**
Estonia	**EE**	Portugal	**PT**
Finland	**FI**	Romania	**RO**
France	**FR**	Sweden	**SE**
Germany	**DE**	Slovenia	**SI**
Greece	**GR**	Spain	**ES**
Hungary	**HU**	Switzerland	**CH**
Ireland	**IE**	United Kingdom	**UK**

Table 3.3: ESA member states standard acronyms

In terms of actions, for what concerns the "control" of the activities development, ExPeRT can only act as a supervisor of the ongoing development reported by the RO, being the RO the interface in the middle between client (ExPeRT) and the supplier (the winning company).
The term "control" is therefore addressed to the control of the RO input in PRONTO, which is the only domain under ExPeRT influence.

Given the inconsistency database generated in *PRONTO Global Monitoring*, the interface in Fig.3.22 is produced and displayed. The funding idea is to send emails to the RO with automatic messages tuned accordingly to the inconsistencies detected.
There are mainly 2 sections in the tab: the first one is the inconsistency database imported from the *PRONTO Global Monitoring* tab (Fig.3.22), while the second is the automatic email generator (Fig.3.23).

The activities for which inconsistencies have been detected are imported from the list of the *PRONTO General Monitoring*. In such a way the inconsistency list with related data and RO is displayed and available.

With the need of opportunely notice the RO of the detected inconsistencies the user can insert in the search toolbar the activity reference or title, and TMT is automatically fetching the corresponding data and RO email associated (see Fig.3.23). The *Automatic Email Generation* button is then implemented, and it embeds an automatic generation of an email, to the corresponding RO of the activity, as well as a specific text tuned on the inconsistency flag. The email is then displayed in the tool, and the drafting can be performed in Excel directly. Finally the Email can be sent from Excel, in fact via VBA

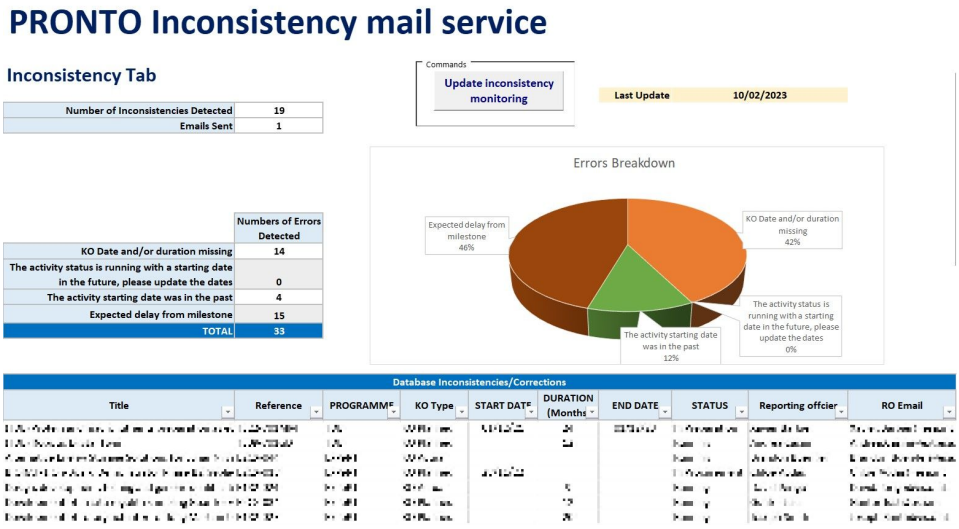


Figure 3.22: *PRONTO Email-Inconsistencies* part 1

the Outlook application is interfaced with the account of the user: the ESA account also works.

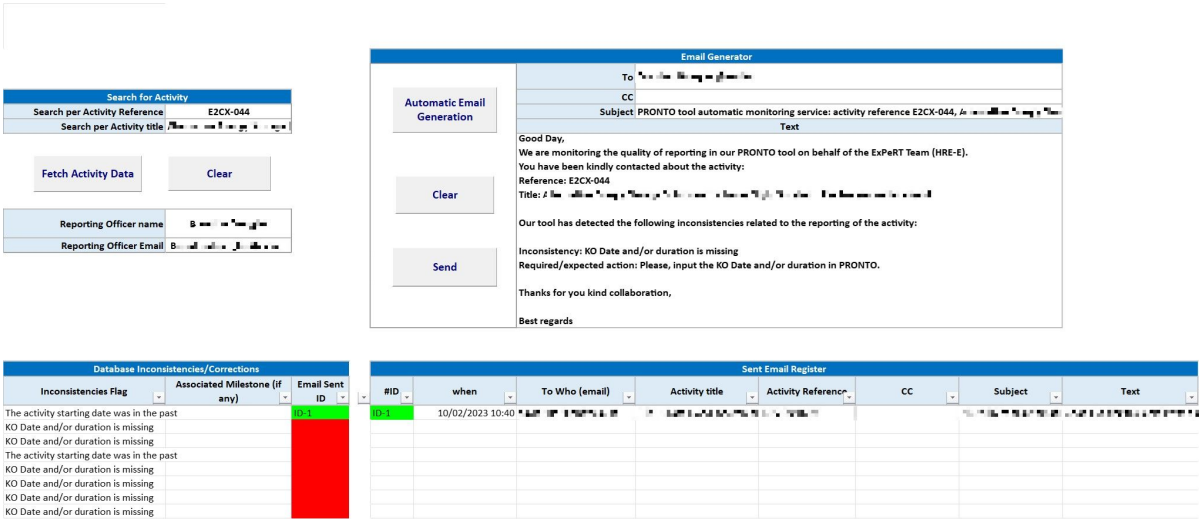


Figure 3.23: *PRONTO Email-Inconsistencies* part 2

Once ExPeRT has sent the correction email to the RO, the platform is then storing the email sent assigning a unique ID to the activities for which the email has been sent so that it is always possible to know the overall status of the messages already sent, and more people can use the platform without sending the same emails twice. The green and red flags are then used to mark the inconsistencies which have been (or not) corrected.

PRONTO Single Monitoring

All the previous tabs were providing a global overview of PRONTO in terms of budget per country, development in time (gantt and roadmaps) and development status with correlated delays and inconsistencies.

Regarding the monitoring of the single activities, the only operations which could be performed before was the single activity tab in PRONTO. Merging the tools introduced for the full activities list the *PRONTO Single Monitoring* in Fig.3.24 is generated, at the scope of providing the overview on the full procurement, planning and implementation cycle of each activity.

The user interface is including the 3 main sections of the previous tabs: in the top right the activity fiche is displayed, the contractors budget share and inconsistency detected in the top right, and the overall procurement, implementation and milestones achieved gantt in the bottom right. For what concerns the last section, the overall gantt life-cycle is providing now the notional timeline in a graphical interface which was never displayed before.

3.4. TMT Part 2: Exploration Technology Database

TMT Part 2 deals with the technology activities storage. Once the activities have been implemented and correctly concluded, the TRL is increased and the activity takes part in the ESA "knowledge bank". As it was anticipated, a proper data storage which daily collects and updates the technology activities internal to the agency doesn't exist. [4] The funding idea is therefore the implementation of such database, with the feature of being live-connected to PRONTO as to automatically update its content. The logical flowchart is shown in Fig.3.25.

Following the Technology Flowchart steps, the TMT Part 2 can be logically decomposed in 5 main parts:

1. Requirements;
2. Data sources;
3. The ExPeRT Technology Database;
4. Data analysis and monitoring;
5. GTDM and GERs (beyond the scope of the thesis).

[4] At list that is also involving ExPeRT.

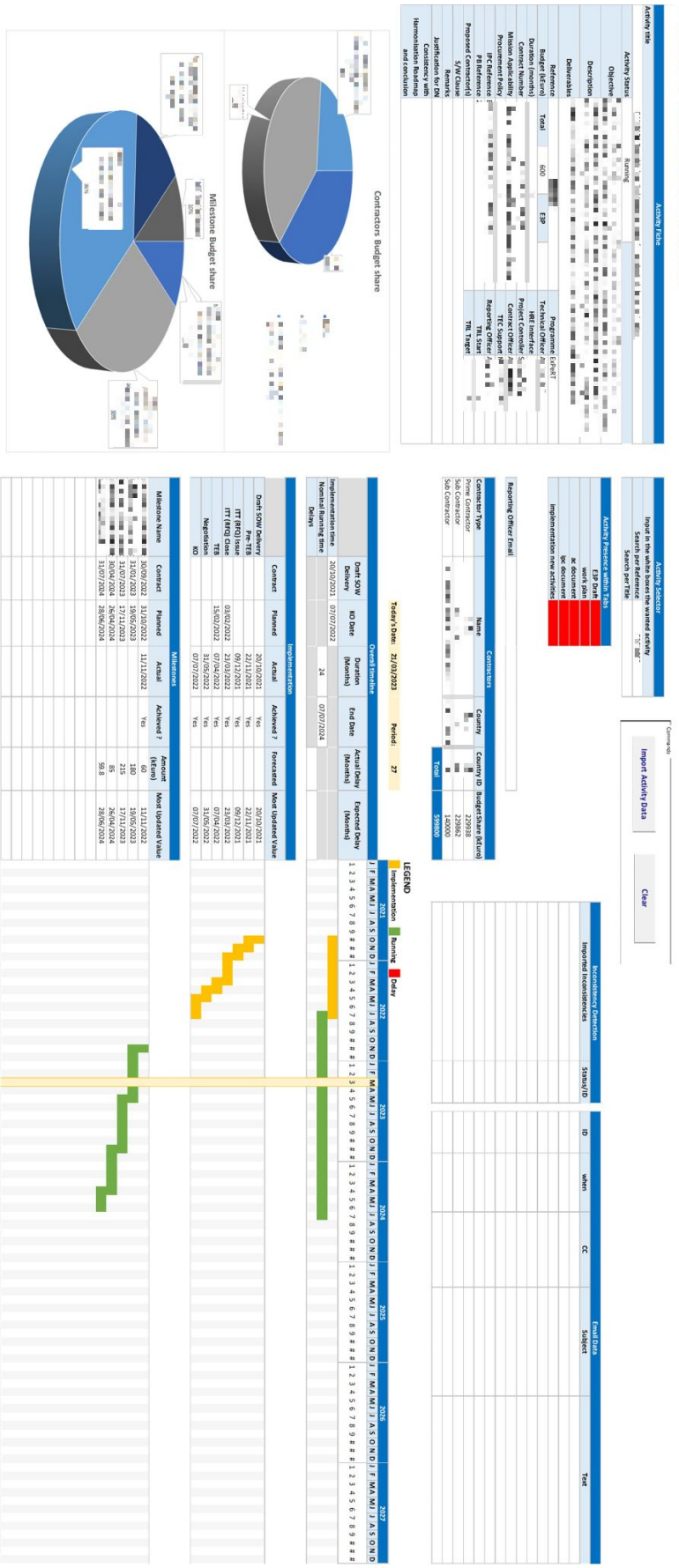


Figure 3.24: *PRONTO Single Monitoring* tab

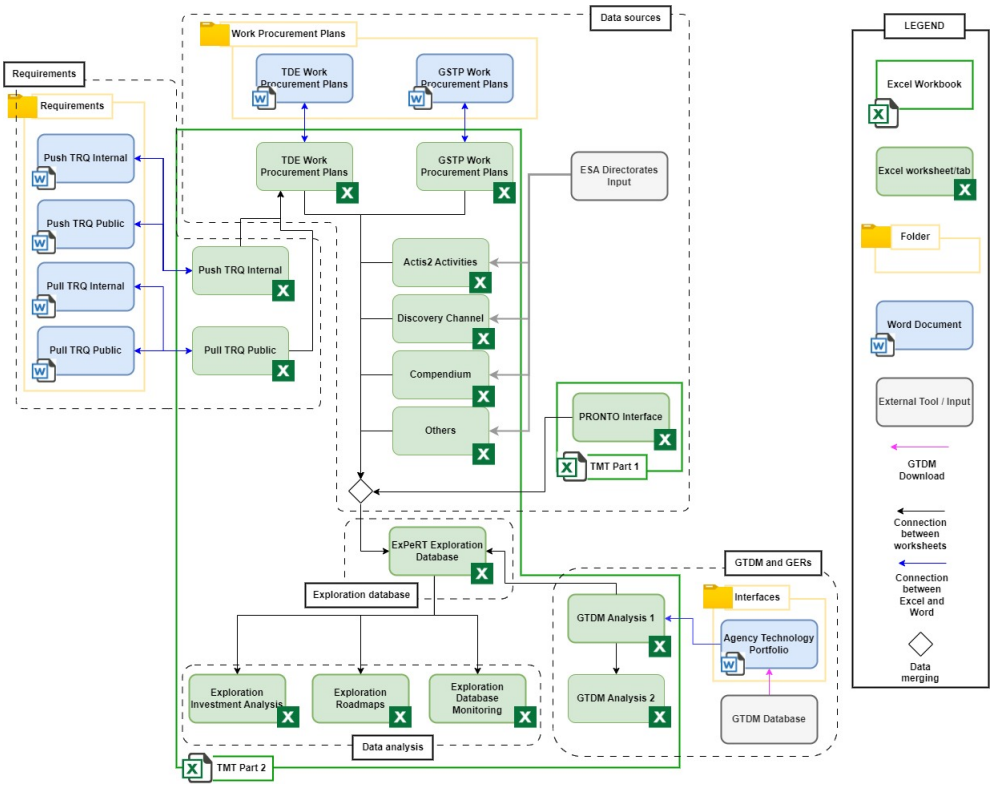


Figure 3.25: TMT Part 2 logical architecture

NOTE: the results and analysis performed in this section are based on the activities belonging to the *ExPeRT 2022 Exploration Technologies Compendium* [8]. All the analysis are therefore addressing published information by ESA and only addressable to the Compendium itself.

3.4.1. Requirements

ExPeRT is responsible of formulating the requirements for exploration. At this purpose the *Pull TRQ Fiche* and *Push TRQ Fiche* tabs have been created. Following the same concept of the *E3P Draft Activities* tab the requirements tab is connected to the Word documents containing the requirements fiches and from the Excel buttons the operations are performed. The corresponding command bar for the Push requirements (exactly the same holds for the Pull one) is shown in Fig.3.26.

Before publicating the requirements, they are drafted internally to the agency, therefore two templates are present: one for the internal requirements and one for the public one. At this purpose Excel is used as a container of both templates, highlighting the difference by means of two flags, each of them assigned to one of the two templates.

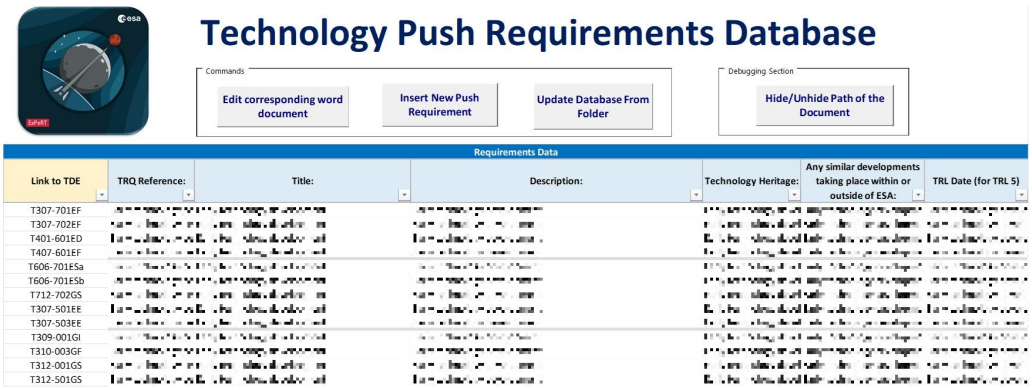


Figure 3.26: *Push TRQ Fiche*

Requirements linkage Another interesting idea formulated during the development is the linkage to the activities. The ExPeRT activities not funded by ExPeRT are financed by TDE. The TDE activities are linked to the ExPeRT requirements, both push ans pull. Sometimes in the fiche the requirement TRQ is present, some other times it is not.
For this reason the tab is including an automatic link, also draftable by hand, for which if the TDE activity is including the TRQ fiche in the field, the linkage is automatic; in case there is no reference, the user is allowed to manually draft the link simply fetching the activity reference in the linkage column.

3.4.2. Database data sources

The procurement and implementation cycle is only followed by ExPeRT for what concern the ExPeRT, CS3 and MREP activities. All the other programs are lost in the implementation.
For this reason the formulation of a database containing all the activities coming from different programs is the funding idea which brought to the implementation of TMT Part 2. The programs included in TMT are: ExPeRT, GSTP, TDE, MREP, CS3, Discovery, TIA, NAV, Spaceship.
Each of these programmes presents its own data source, and TMT is merging all the activities in what was called ExPeRT Technology Database. Combining the data sources of the activities there is a total of 7 of them from which the database is generated (see Fig.3.27).

Compendium

Every year ExPeRT is responsible of publishing the exploration technology compendium, which represent the list of technology activities relevant for exploration from different pro-

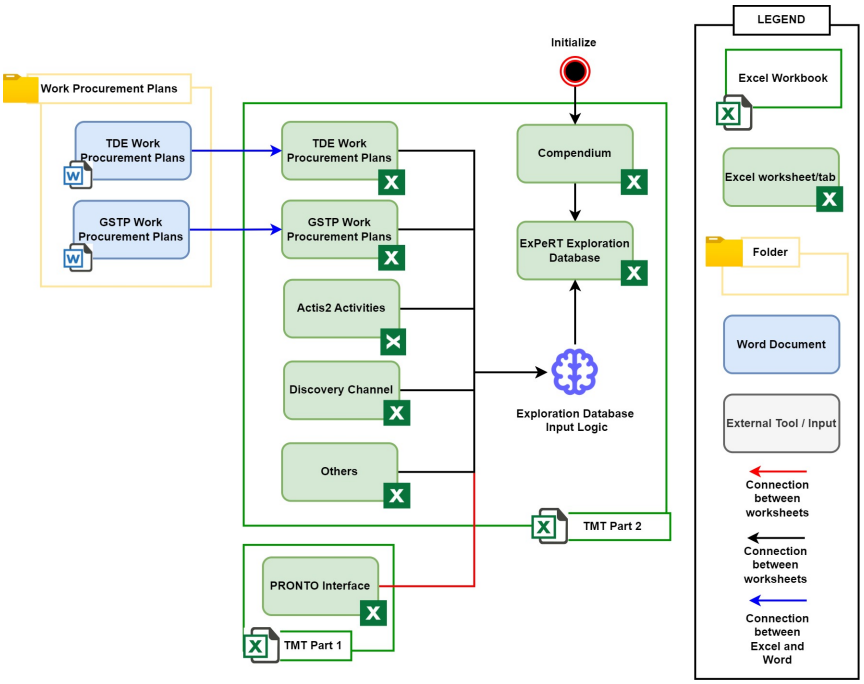


Figure 3.27: Data sources of the Exploration Database

grams internal to the agency. It represents the last update list of TDE, GSTP and ExPeRT activities (but also includes other programmes conducting with technology developments that are considered relevant for Exploration applications). The whole compendium list is embedded in the database in the *Compendium* tab, representing the first data source. The screenshot of the compendium is shown in Fig.3.28.

Activity ID	SD	Technology Area	Title	Status	E3P Budget (k€)	Start TRL	Target TRL	Prime Contractor (Country)	Destination
E1X2-044	EXP	1. Propulsion	Development of Huracan, a new cryogenic LOX/methane engine for exploration missions – First Phase	Under Proc.	495	3	4		Moon
E2C3-027a	EXP	1. Propulsion	Advance Procurement of materials and tooling for EL3 propellant tank dome forgings	Under Proc.	500	N/A	N/A		Moon

Figure 3.28: Exploration Technology Compendium screenshot [8]

It is important to notice how only a few information are available from the compendium with respect all the one present in the activity fiches.

The compendium list being published once per year is not update daily. In facts the activities present in the compendium are only made public in January/February, collecting all the R&D of the previous year. For this reason starting with the inclusion in the database of the compendium, this tab won't be modified anymore. It is simply representing a first "version" of the ExPeRT Technology Database. The idea is then to use the ExPeRT

Technology Database as technologies collector, which in turn will is embedding the old compendium, and in doing so, the new compendium.

TDE and GSTP Work-Procurement Plan

Following the exact same procedure of the E3P Work/Procurement Plan, for what concerns TDE and GSTP the procurement cycle retraces the same step, following the formulation of a Work Plan and then a Procurement plan. It is useful to include the activities belonging to these Work Plans even though they are just starting now the implementation cycle (beware that it is possible that some of them are cancelled or not implemented at the end). In doing so the exact same logic as E3P activities is followed, including one tab for each program connected to the word document source. The tab is not shown being the same as the E3P Activity import.

Actis2 Activities

As it was introduced in Chapter 2 the TDE and GSTP activities are reported inside Actis2 (representing the D/TEC version of PRONTO). It is interesting to include also this data source in order to have the updated list and consequent updated status of the activities belonging to these programs. The direct export of the Actis2 list is requested to the TEC department and included in the *Actis2* tab in Fig.3.29. The request of the list was before performed yearly be ExPeRT, upon the formulation of the new compendium list; same logic follows here, which is also consistent with the approval of the Work Plans of TDE and GSTP (yearly presented to the member states).

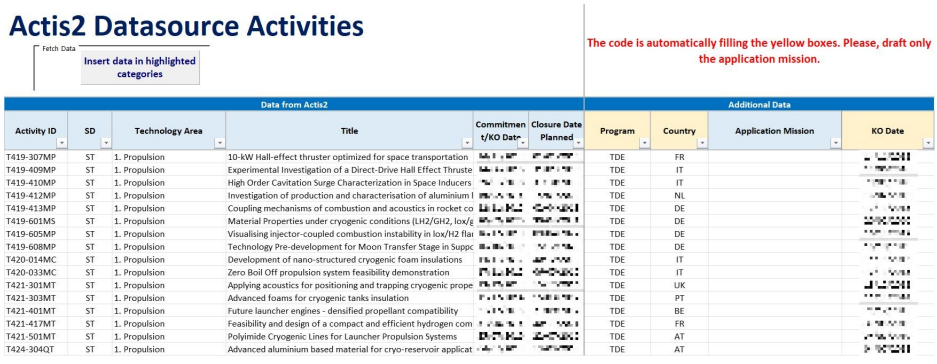


Figure 3.29: *Actis2* tab screenshot

A small consideration has to be made: the export from Actis2 is not exactly matching the format of TMT. for this reason the button is included in order to automatically fetch the country of the prime contractor, the KO date and the program inside the tab. The yellow categories highlight the parts of the Sheet where a manipulation of the data is required

with respect the simple import.

Discovery Channel

ESA is promoting new ideas and initiatives thanks to OSIP (Open Source Innovation Platform). The Discovery funded activities are therefore ideas, promoted by ESA, implemented by different entities between the member states. At this scope the public lists of activities are present on ESA website. Some of the activities are relevant to exploration, therefore included in the platform. The Technology Area has to be manually set, as well as the country to which the prime contractor belongs. The tab in not shown being similar to the Actis2 one.

Others

Given the wide spectrum of applications on which ESA is moving, a "Others" tab is included, in order to fetch in the tool all the activities which are not coming from any of the other data source. It is really useful to have such a capability being the tab used to include eventual old activities, or in general anything which is not embedded in the tool up to now. The activities are then fetched manually in the tab (not shown being a simple Excel to be manually populated).

PRONTO

The last data source is represented by the activities coming from PRONTO: collecting the MREP, CS3 and ExPeRT activities. Being PRONTO connected to TMT Part 1, in order to keep all the activities interface with it under control, it was decided to keep only the Part 1 connected to PRONTO and to interconnect TMT Part 2 with the Part 1, simply retrieving the wanted data. The way it is done is simple: the TMT Part 1 link is present in the *Exploration Technology Database* tab, therefore allowing the tab to access its content. The PRONTO activities tab of TMT Part 1 is then reached, and by simply looping in the list the activities are fetched in the Exploration Database. This connection doesn't require any tab, in fact the *PRONTO Interface* tab of TMT Part 1 is used.

3.4.3. Exploration Technology Database

Now that all the data sources have been introduced, the working idea of the Exploration Database is addressed. As anticipated, the Exploration Database is conceived to be the collection of all the activities coming from the different source, allowing ExPeRT to have a global overview always up to date of the ongoing activities in ESA. The Exploration

Database is generated thanks to a complex code which composes the overlapping of all the 7 data sources. The activities categories and data present in the database are presented in Fig.3.30.

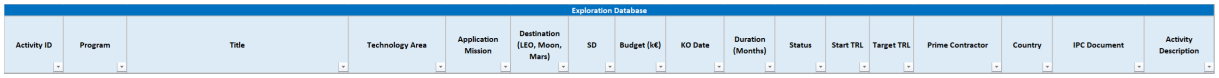


Figure 3.30: *Exploration Technology Database* available categories

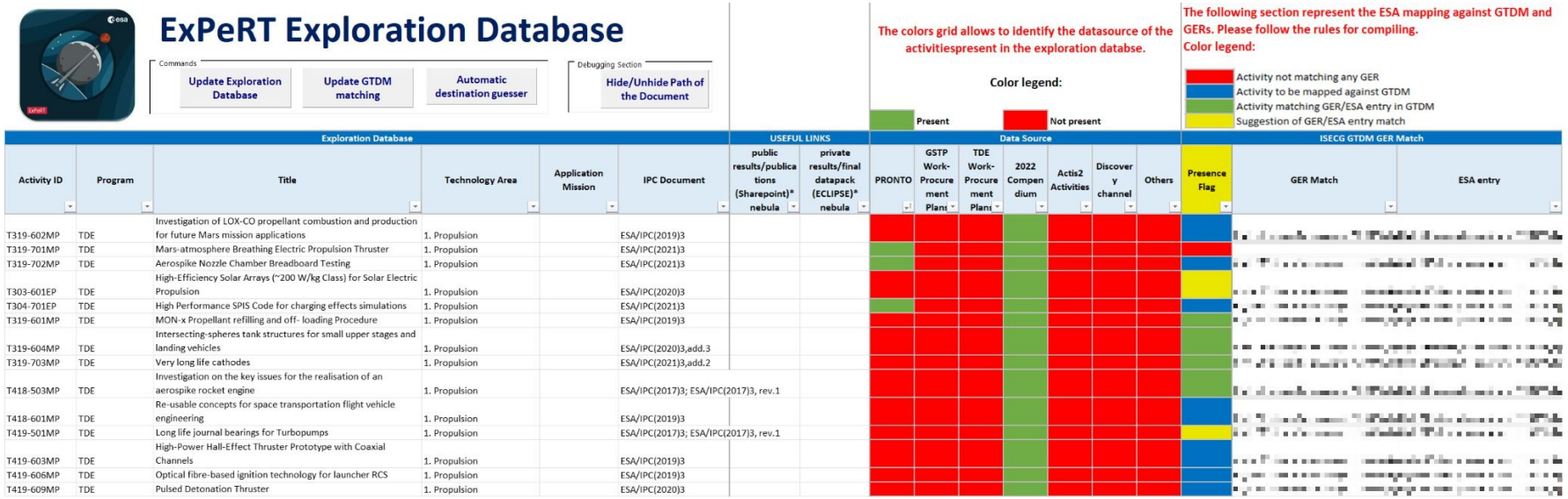
The *KO* date and the *Status* of the activities are the only categories which are present in the Exploration Database, and are updated along the implementation and development of the activities. For this reason the update of these data is always required. On the other hand, the fiche data once the activities are approved are never updated, therefore they do not require continuous update.

Merging all the data is immediately evident how the same activity can be present in more of one data source, in fact simply considering the compendium as skeleton of the Exploration Database, all the activities committed in the past would be also present in the other tabs.
The logic is to make the data of part of the data sources to overwrite others, because some represent the updated state of the latter: the TDE and GSTP Work Plans for example only include in preparation activities, while the further developments of their status is monitored and tracked from the *Actis2* tab.
The 2022 technology compendium represents the skeleton of the Database, meaning that the activities contained in the compendium are imported only the first time in the Exploration Database, when it was firstly implemented and initialized. The logic the database population is explained in Appendix A.

At this stage the activities are then imported in the database composing a simple list which collects everything. The way it works is reference-based. In fact the reference is the only way to be sure that the same activity is not repeated. The interface of the Database is shown in Fig.3.31.

Overall there are 4 main sections in the Exploration Database:

1. the *Exploration database* section, representing the list of activities with the relevant data and categories;
2. the useful links section;
3. the data source grid;
4. the GTDM interface.



ExPeRT Exploration Database

Commands: Update Exploration Database | Update GTDM matching | Automatic destination guesser

Debugging Section: Hide/Unhide Path of the Document

The colors grid allows to identify the datasource of the activitiespresent in the exploration databse.

Color legend: Present / Not present

The following section represent the ESA mapping against GTDM and GERs. Please follow the rules for compiling.

Color legend:
- Activity not matching any GER
- Activity to be mapped against GTDM
- Activity matching GER/ESA entry in GTDM
- Suggestion of GER/ESA entry match

Exploration Database						USEFUL LINKS		Data Source							ISECG GTDM GER Match		
Activity ID	Program	Title	Technology Area	Application Mission	IPC Document	public results/publications (Sharepoint)* nebula	private results/final datapack (ECLIPSE)* nebula	PRONTO	GSTP Work-Procurement Plans	TDE Work-Procurement Plans	2022 Compendium	Actis2 Activities	Discovery channel	Others	Presence Flag	GER Match	ESA entry
T319-602MP	TDE	Investigation of LOX-CO propellant combustion and production for future Mars mission applications	1. Propulsion		ESA/IPC(2019)3												
T319-701MP	TDE	Mars-atmosphere Breathing Electric Propulsion Thruster	1. Propulsion		ESA/IPC(2021)3												
T319-702MP	TDE	Aerospike Nozzle Chamber Breadboard Testing	1. Propulsion		ESA/IPC(2021)3												
T303-601EP	TDE	High-Efficiency Solar Arrays (~200 W/kg Class) for Solar Electric Propulsion	1. Propulsion		ESA/IPC(2020)3												
T304-701EP	TDE	High Performance SPIS Code for charging effects simulations	1. Propulsion		ESA/IPC(2021)3												
T319-601MP	TDE	MON-x Propellant refilling and off- loading Procedure	1. Propulsion		ESA/IPC(2019)3												
T319-604MP	TDE	Intersecting-spheres tank structures for small upper stages and landing vehicles	1. Propulsion		ESA/IPC(2020)3,add.3												
T319-703MP	TDE	Very long life cathodes	1. Propulsion		ESA/IPC(2021)3,add.2												
T418-503MP	TDE	Investigation on the key issues for the realisation of an aerospike rocket engine	1. Propulsion		ESA/IPC(2017)3; ESA/IPC(2017)3, rev.1												
T418-601MP	TDE	Re-usable concepts for space transportation flight vehicle engineering	1. Propulsion		ESA/IPC(2019)3												
T419-501MP	TDE	Long life journal bearings for Turbopumps	1. Propulsion		ESA/IPC(2017)3; ESA/IPC(2017)3, rev.1												
T419-603MP	TDE	High-Power Hall-Effect Thruster Prototype with Coaxial Channels	1. Propulsion		ESA/IPC(2019)3												
T419-606MP	TDE	Optical fibre-based ignition technology for launcher RCS	1. Propulsion		ESA/IPC(2019)3												
T419-609MP	TDE	Pulsed Detonation Thruster	1. Propulsion		ESA/IPC(2020)3												

Figure 3.31: *Exploration Technology Database*

***Exploration database* list** The *Exploration database* list represent the database itself. It is collecting all the activities and relevant categories 3.30. The *Destination*, *Application Mission* and *Technology Area* are used in order to perform analysis on missions or categories once the database is populated, in fact TMT part 3 will address this task 4. Merging multiple data sources, more and more categories are populated, being each data source representative of some of them.

The excel filters are really useful at the purpose of perform research within the database given the possibility of filtering multiple information from the same list. Regarding the completeness of the database, some data are missing being not part of the fiche (for example the KO date is only present if the activity comes from PRONTO, Actis2 or Discovery). At this purpose some macros are build in order to automatically guess them when possible: a simple algorithm of destination recognition based on the description has been implemented. In general, the more information are available, the more precise and complete will be the analysis and output that can be produced from the tool.

Useful links The useful links section is used to include in the tool mainly two type of links: the first one is associated with the public information of the activity, therefore web pages or results; while the second column is a direct link to the data packs and ESA internal material to the same activity. This is extremely useful when used internally in ExPeRT: the activity of interest within the database can directly send the user to the data packs describing the deliverables and SoW of the activity providing technical information on the results and descriptions.

Data source grid Being seven the overall number of data sources present, and given the possibility for each activity of coming from multiple destination, a simple green and red flag is implemented in order to have an immediate and visual overview of where the activity data come from. The data source grid is also useful in case where an activity is lost between the tabs, in fact in the activity is not present in the database it means that no data source could detect it, therefore turning the full line red.

GTDM Interface The last section is the Global Technology Development Map interface, but the discussion and working logic is beyond the scope of the thesis..

3.4.4. Monitoring and Data Analysis

Once the database is formed and daily updated the live analysis can be performed. There are mainly 4 interesting analysis performed:

1. the global database monitoring in term of programs and activity status;
2. the investment analysis;
3. the roadmaps and developments;
4. the GTDM analysis.

Exploration Database Monitoring

The *Exploration Database Monitoring* tab is used in order to give a global overview of the database status. There are two main internal sections.

Activities Status The first is the *Activities status* per program, shown in Fig.3.32.

Figure 3.32: Activities Status in *Exploration Database Monitoring*

All the activities are broken down per program and per status in order to give an insight on the number of activities running, and the one already closed, with the possibility of breaking them down per single program, and vice-versa. Applying the filter for the ExPeRT case, it is immediate to see that 40% of the ExPeRT activities is running, while considering the overall database, only the 18% of the whole activity list is belonging to ExPeRT, and running.

Missing Data Monitoring Same categorization per program is kept in the second part, but here the objective is the database completeness. It is useful to know which are the programs which are missing more data and which are the kind of data which are less

populated, and this is used to rise flags and address ExPeRT where are the "problems" in term of lack of data (see Fig.3.33).

Monitoring of Missing Data

	Missing Data per Program								
	ExPeRT	CS3: Lunar Robotic Exploration	TDE	GSTP	MREP	Discovery	Spaceship	NAV/TIA	Others
Technology Area									
Application Mission	70	20	330	59					
Destination (LEO, Moon, Mars)									
SD									
Budget (k€)									
KO Date	70	20	91	4					
Duration (Months)	27	8	39	1					
Status									
Start TRL									
Target TRL									
Prime Contractor	28	10	67	5					
Country	30	10	68	5					
IPC Document									

Total missing		
Number of Total Missing	Relative Percentage between missing data	Percentage of missing w.r.t. ESA total number
0	0.00%	0.00%
479	49.79%	100.00%
0	0.00%	0.00%
0	0.00%	0.00%
0	0.00%	0.00%
185	19.23%	38.62%
75	7.80%	15.66%
0	0.00%	0.00%
0	0.00%	0.00%
0	0.00%	0.00%
110	11.43%	22.96%
113	11.75%	23.59%
0	0.00%	0.00%

Figure 3.33: Missing Data in *Exploration Database Monitoring*

From Fig.3.33 it's immediate to notice how the application mission in basically missing in all the database, and this is given by the fact that the information is missing in most of the fiches and currently not present in PRONTO. This analysis is therefore used to suggest the updates to the full life-cycle and current instrument in use; the manual data fetching can be performed according to the main missing spots.

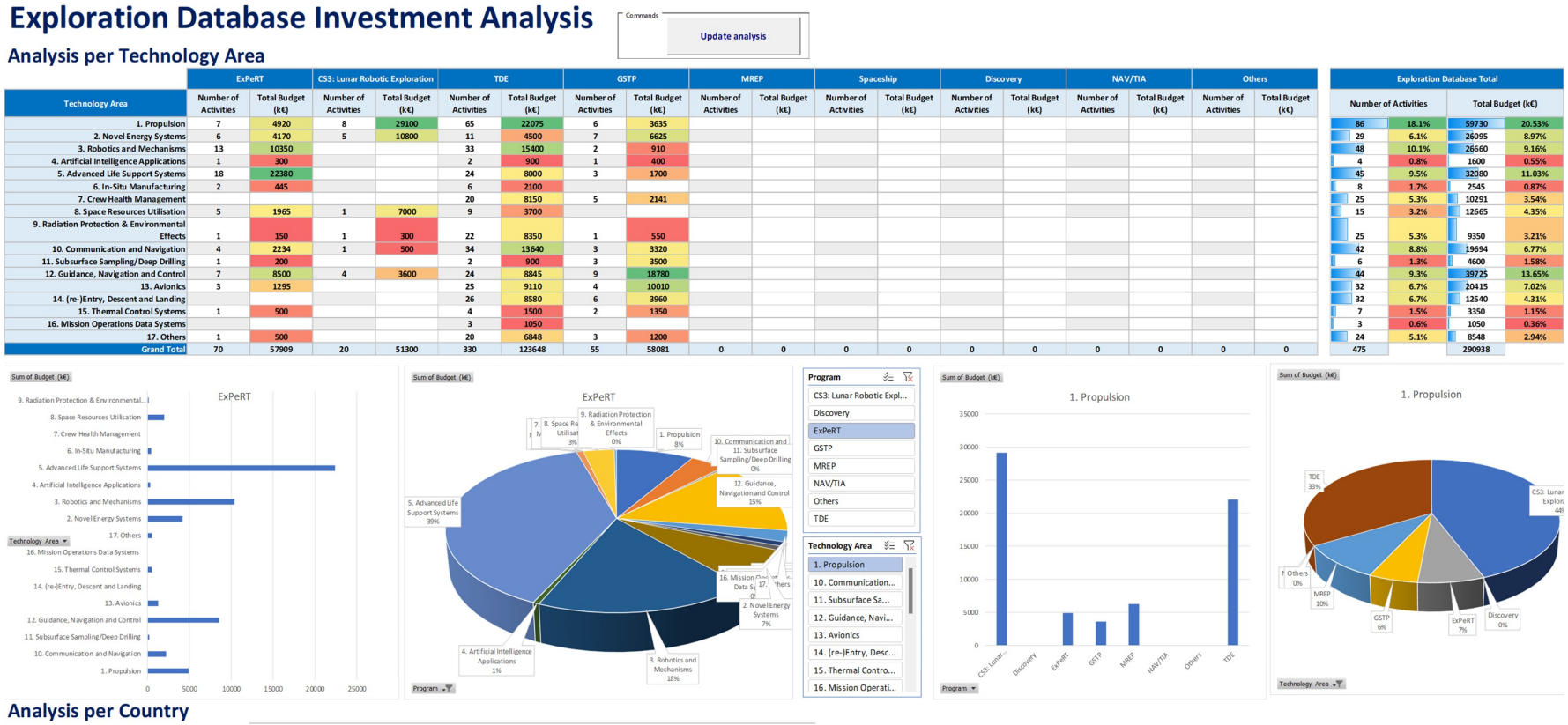
Exploration Investment Analysis

One of the most important analysis to be performed is the investment analysis, performed in *Exploration Investment Analysis*. It is essential for ESA to know where the budget are invested and how. The full database, containing the budget column for each activity allows to give useful insight. Again also here two are the main analysis that can be performed.

Investment per Technology Area As the technologies are broken down per technology area, each of them can be specifically analyzed in order to see where each program is investing more. Fig.3.34 provides the overview for the whole programs.

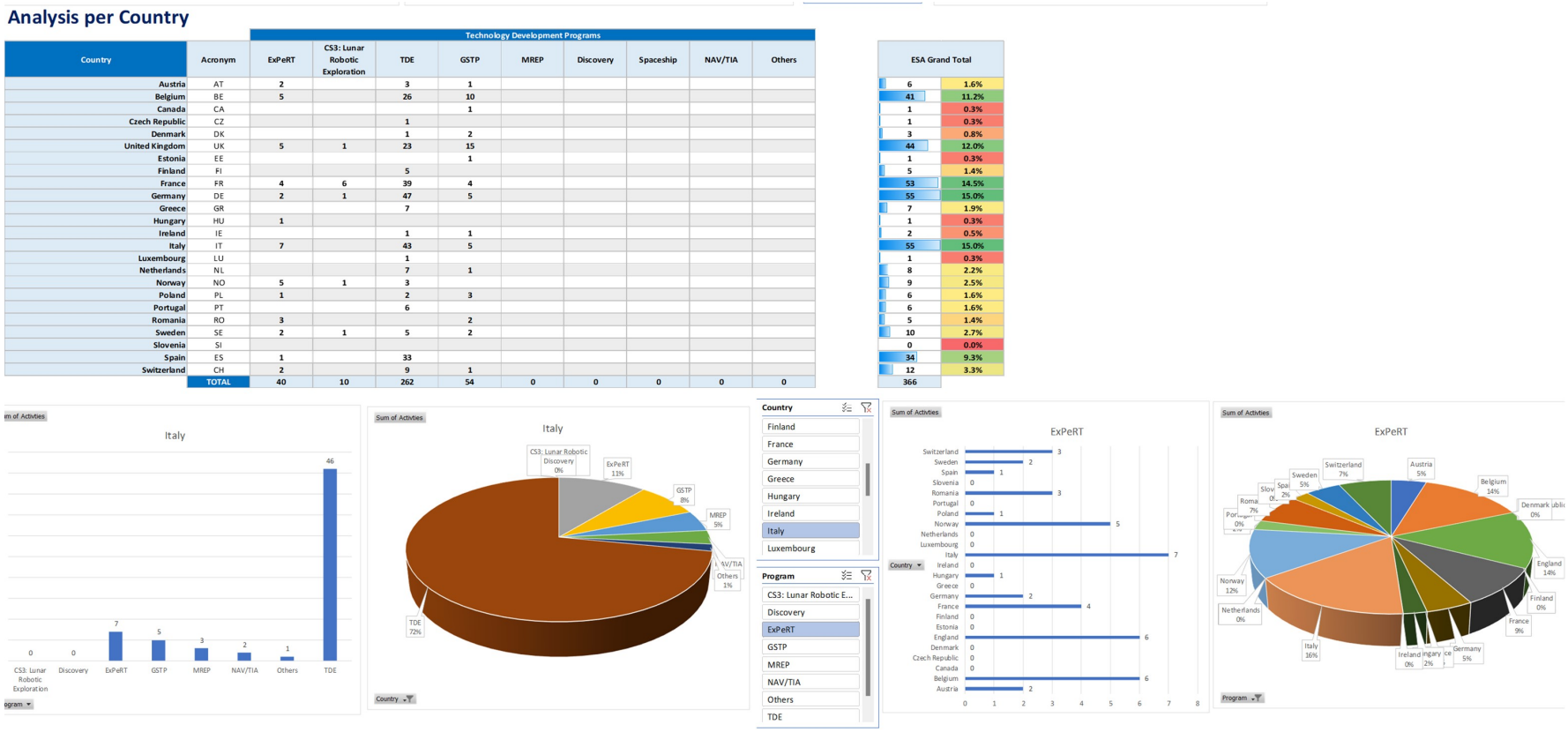
The pivot charts allow to both filter results on the programs and the single technology area. It is useful to apply the programme filter to analyze the programmes which are more contributing to each specific area. Focusing on the program filter, applying the filters to select only ExPeRT it emerged that the 38% of ExPeRT activities is addressing Advanced Life Support Systems activities, followed by the 18% covered by Robotics and Mechanisms and the 15% in GNC.

Geographical analysis The investment analysis is also performed applying the breaking down of the activities per country. The geography analysis belonging to *Exploration Investment Analysis* is shown in Fig.3.35.



Technology Area	ExPeRT		CS3: Lunar Robotic Exploration		TDE		GSTP		MREP		Spaceship		Discovery		NAV/TIA		Others		Exploration Database Total			
	Number of Activities	Total Budget (k€)	Number of Activities	Total Budget (k€)	Number of Activities	Total Budget (k€)	Number of Activities	Total Budget (k€)	Number of Activities	Total Budget (k€)	Number of Activities	Total Budget (k€)	Number of Activities	Total Budget (k€)	Number of Activities	Total Budget (k€)	Number of Activities	Total Budget (k€)	Number of Activities		Total Budget (k€)	
1. Propulsion	7	4920	8	29100	65	22075	6	3635											86	18.1%	59730	20.53%
2. Novel Energy Systems	6	4170	5	10800	11	4500	7	6625											29	6.1%	26095	8.97%
3. Robotics and Mechanisms	13	10350			33	15400	2	910											48	10.1%	26660	9.16%
4. Artificial Intelligence Applications	1	300			2	900	1	400											4	0.8%	1600	0.55%
5. Advanced Life Support Systems	18	22380			24	8000	3	1700											45	9.5%	32080	11.03%
6. In-Situ Manufacturing	2	445			6	2100													8	1.7%	2545	0.87%
7. Crew Health Management					20	8150	5	2141											25	5.3%	10291	3.54%
8. Space Resources Utilisation	5	1965	1	7000	9	3700													15	3.2%	12665	4.35%
9. Radiation Protection & Environmental Effects	1	150	1	300	22	8350	1	550											25	5.3%	9350	3.21%
10. Communication and Navigation	4	2234	1	500	34	13640	3	3320											42	8.8%	19694	6.77%
11. Subsurface Sampling/Deep Drilling	1	200			2	900	3	3500											6	1.3%	4600	1.58%
12. Guidance, Navigation and Control	7	8500	4	3600	24	8845	9	18780											44	9.3%	39725	13.65%
13. Avionics	3	1295			25	9110	4	10010											32	6.7%	20415	7.02%
14. (re-)Entry, Descent and Landing					26	8580	6	3960											32	6.7%	12540	4.31%
15. Thermal Control Systems	1	500			4	1500	2	1350											7	1.5%	3350	1.15%
16. Mission Operations Data Systems					3	1050													3	0.6%	1050	0.36%
17. Others	1	500			20	6848	3	1200											24	5.1%	8548	2.94%
Grand Total	70	57909	20	51300	330	123648	55	58081	0	0	0	0	0	0	0	0	0	0	475		290938	

Figure 3.34: Investment analysis per technology area



Analysis per Country

Country	Acronym	Technology Development Programs									ESA Grand Total	
		ExPeRT	CS3: Lunar Robotic Exploration	TDE	GSTP	MREP	Discovery	Spaceship	NAV/TIA	Others		
Austria	AT	2		3	1						6	1.6%
Belgium	BE	5		26	10						41	11.2%
Canada	CA				1						1	0.3%
Czech Republic	CZ			1							1	0.3%
Denmark	DK			1	2						3	0.8%
United Kingdom	UK	5	1	23	15						44	12.0%
Estonia	EE				1						1	0.3%
Finland	FI			5							5	1.4%
France	FR	4	6	39	4						53	14.5%
Germany	DE	2	1	47	5						55	15.0%
Greece	GR			7							7	1.9%
Hungary	HU	1									1	0.3%
Ireland	IE			1	1						2	0.5%
Italy	IT	7		43	5						55	15.0%
Luxembourg	LU			1							1	0.3%
Netherlands	NL			7	1						8	2.2%
Norway	NO	5	1	3							9	2.5%
Poland	PL	1		2	3						6	1.6%
Portugal	PT			6							6	1.6%
Romania	RO	3			2						5	1.4%
Sweden	SE	2	1	5	2						10	2.7%
Slovenia	SI										0	0.0%
Spain	ES	1		33							34	9.3%
Switzerland	CH	2		9	1						12	3.3%
	TOTAL	40	10	262	54	0	0	0	0	0	366	

Figure 3.35: Investment analysis per country

It can be immediately seen that Italy and Germany are prevailing, followed by France and UK. Filtering again for programme and applying the filter to ExPeRT activities only, Italy results to be the the most winning country with 7 activities over 40 overall (currently representing the 17.5%). Following the same logic applying the country filter to Italy, it can be seen how the 72% of the Italian contracts in turn are belonging to TDE programme, while only the 18% belong to ExPeRT: this is due to the higher amount of contract that TDE is opening every clear (the budget in fact is considerably bigger).

Exploration Roadmaps

The Exploration Database is also used to generate exploration roadmaps. Merging all the data the KO dates and duration of the activities are densely populated. Being the KO dates of the activities not public, the Exploration Roadmaps cannot be shown, but the template follows exact the same format as for the *PRONTO Roadmaps* in Fig.3.3.4. The user-case in Chapter 4 is displaying the roadmaps for the case study in analysis.

4 | The European ISRU technologies

The Technology Process Flowchart is almost fully covered by TMT Part 1 and TMT Part 2, reaching the Technology Database and Analysis level. The full technology cycle from its definition up to the implementation and storage, has been in fact broken down and implemented in TMT.
The last task entrusted by ExPeRT is the public outreach of the yearly results of the team. During the development of TMT it emerged that an effective tool capable of providing support in the publication of results it wasn't existing.
At the purpose of showing the full functionalities of TMT Part 3 and how the whole TMT tool is supporting the procurement and implementation process, a practical user case is taken in analysis.

4.1. ISRU Technologies in TMT

Nowadays always more focus is given to the In Situ Resource Utilization area, in fact the ISRU area is conceived as a key factor enabling human exploration on other planets and moons: it is also included in the Global Exploration Roadmap [26].
In 2020 ExPeRT published the In-Situ Resource Utilisation Campaign Roadmap [7], presenting a general overview of system and technology activities at ESA related to space resources and its potential utilisation.
It ranges from past, present and potential future activities under planning, throughout a variety of funding schemes according to specific maturity levels and in a coordinated way. It serves the purpose of raising awareness of the overall programme of work and effort towards the understanding and potential utilisation of space resources.

The ISRU area is taken as user case applied to TMT, from the CDF studies up to the activities inclusion in the Exploration Database. TMT Part 3 idea and architecture will be then introduced, at the scope of updating the ISRU Campaign Roadmap and introducing the new categorization chosen.

Following the two possible types of implementation, ExPeRT can either directly draft the activities funded by its own budget, or collaborate with D/TEC for the formulation of an activity which is linked to ExPeRT requirements, but part of the TDE Work/Procurement Plans. A practical example of both implementations is given.

4.1.1. ExPeRT ISRU activity: DIGGER

In the framework of the ISRU area, as it will be shown in Fig.4.11 the first part of the process is the acquisition of the feedstock. Hence, in Period 1 ExPeRT approved the implementation of the activity *Development of In-situ regolith sampling Gear for GenerousExcavation of Regolith (DIGGER)*, associated the with reference *E1X2-042*.
A contract extension for this activity is proposed in Period 2, with the activity *Development of In-situ regolith sampling Gear for Generous Excavation of Regolith (DIGGER) - Complement* and reference *E2CX-034*, included in the 2022 Compendium [8]. All the technology life-cycle in simulated within TMT.

Procurement Cycle

The procurement cycle is depicted in Fig.4.1.

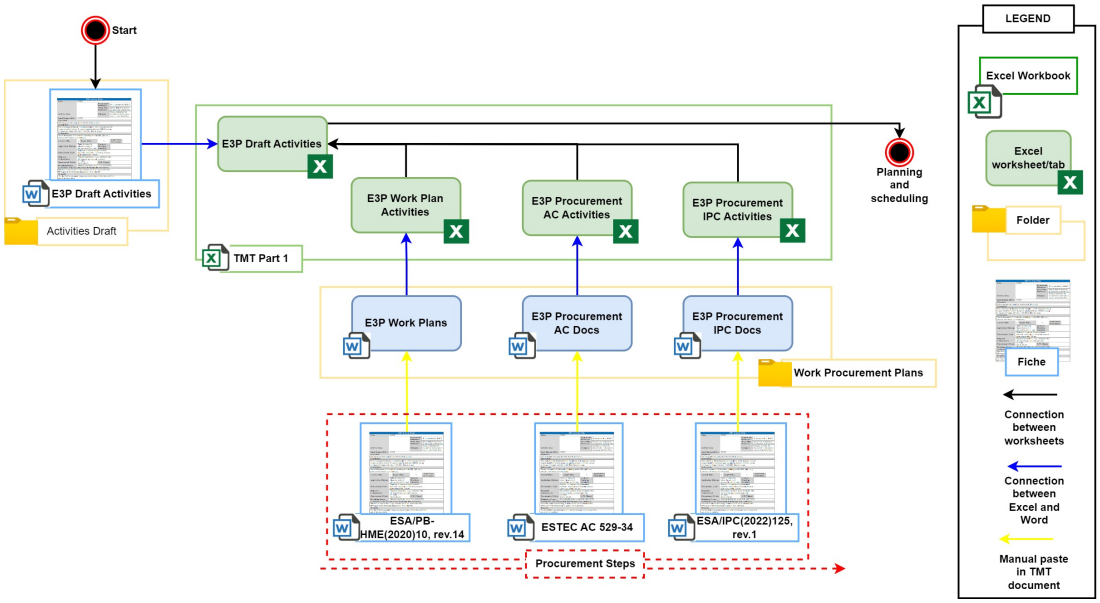


Figure 4.1: Activity E2CX-034 procurement cycle in TMT

The activity fiche is initially proposed, drafted, included in *E3P Draft Activities* Word document and imported in TMT *E3P Draft Activities* tab. Subsequently the activity takes part in the E3P Work Plans and is presented to PB-HME as part of the document *ESA/PB-HME(2020)10, rev.14* [10] for approval.

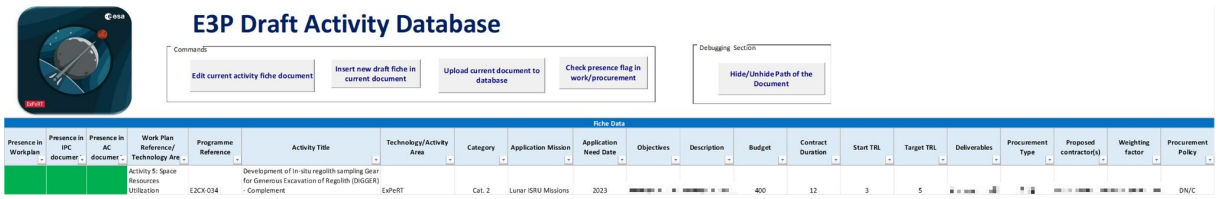


Figure 4.2: Activity E2CX-034 within *E3P Draft Activities* tab in TMT

Upon approval it is then passing to the AC level, and included in the *ESTEC AC 529-34* document [11]. The third and last stage is the presentation of the activity to the IPC, as part of the *ESA/IPC(2022)125,rev.1* Procurement Plan [12]. Once the IPC level is reached and the Work/Procurement Plans have been included in TMT, all the procurement flags turn green (see Fig.4.2).

Implementation

The scheduling and manpower planning can begin, in fact the activity is then imported in the *Implementation New Activities* sheet in TMT Part 1. In this case being the activity part of a contract continuation supplementing another previously existing, the procurement is a DN type, therefore according to 3.1 the overall implementation is supposed to last 16 weeks, as no ITT is open. For the purpose of this example the assumption made is that the planned, contract and actual starting date of the implementation steps coincide. Lastly, the milestones are supposed to be the one in Tab.4.1.

E2CX-034 Assumed Milestones	Budget (k€)
Milestone 1	100
Milestone 2	100
Milestone 3	200

Table 4.1: Activity E2CX-034 Assumed Milestones

As the IPC dates back to the 9th of June 2022, the Draft SoW is assumed to be the 1st of September 2022. From *Implementation New Activities* tab the manpower and the draft SoW date are fetched in TMT, and the implementation dates are then estimated from the procurement type. The estimated KO date (that in this example coincides with the actual one) is the 22/12/2022 (Fig.4.3).

The activity is subsequently uploaded to PRONTO via *Activities PRONTO Export* workbook. The PRONTO download is operated by TMT and the activity is included in *PRONTO Interface* in TMT, as well as the associated milestones in *PRONTO Mile-*

Manpower Planning						Contract Implementation Forecast							
Technical Officer	Reporting Officer	Contract Officer	Project Controller	ExPeRT Interface	Chairperson (if TDE)	Draft SoW Date	Pre-TEB	ITT/RFQ issue	ITT/RFQ close	TEB	Negotiation	KO	Forecast End of Activity
Person 1	Person 2	Person 3	Person 4	Person 5	-	01/09/2022	15/09/2022	06/10/2022	03/11/2022	13/11/2022	01/12/2022	22/12/2022	22/12/2023

Figure 4.3: Scheduling and manpower of activity E2CX-034 in TMT

stones Interface. The milestones date have also been assumed and included in Fig.4.4, part of the *PRONTO Milestones Interface* worksheet.

PRONTO Milestones Interface

Commands: Import PRONTO Milestones | Debugging Section: Hide/Unhide Path of the Document

Please: make sure you have opened and synchronized expert milestones excel interface with sharepoint before performing this operation.

Last Import from PRONTO milestone excel: 24/03/2023

Data from PRONTO Milestones									
Reference	Activity title	Activity Status	Programme	Milestone Name	Contract Date	Planned Date	Actual Date	Amount (kEuro)	Achieved?
E2CX-034	Development of In-situ regolith sampling Gear for Generous Excavation of Regolith (DIGGER) - Complement	Running	ExPeRT	Milestone 1	22/04/2023	22/04/2023	22/04/2023	100	
E2CX-035	Development of In-situ regolith sampling Gear for Generous Excavation of Regolith (DIGGER) - Complement	Running	ExPeRT	Milestone 2	22/08/2023	22/08/2023	22/08/2023	100	
E2CX-036	Development of In-situ regolith sampling Gear for Generous Excavation of Regolith (DIGGER) - Complement	Running	ExPeRT	Milestone 3	22/12/2023	22/12/2023	22/12/2023	200	

Figure 4.4: E2CX-034 assumed milestones in *PRONTO Milestones Interface*

Once the KO date is then reached, the activity can start. At the purpose of showing the *TMT Single Monitoring* functionality Fig.4.5 is displaying the overall assumed implementation steps.

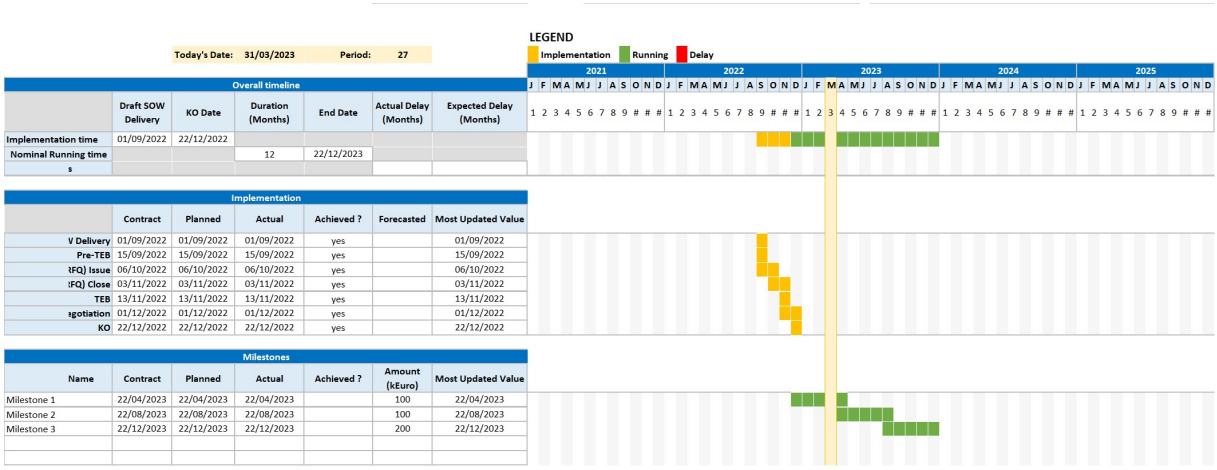


Figure 4.5: E2CX-034 assumed gantt in *PRONTO Single Monitoring*

Finally, from TMT Part 2 the Exploration Database can be updated to include the new activity from the *PRONTO Interface* worksheet, being one of the seven data sources of the database itself.

4.1.2. TEC ISRU activity: ARMADILLO

The definition, implementation and data storage of an ISRU-related activity implemented in collaboration with D/TEC is shown.

A.R.M.A.D.I.L.L.O. CDF study

Data return from robotic spacecraft at Mars suggest potential abundances of water-ice may be found in the near subsurface at accessible locations and latitudes for future human missions. These findings have significant implications for two of the most compelling reasons for Mars exploration; searching for life elsewhere in the universe and preparing to send the first humans to another planet.
The subsurface of Mars is an ionising radiation free environment and provides conditions that allow water to exist in a stable form, which may in turn provide nice habitable conditions for past (and potentially present) microorganisms [9].
To date subsurface ice deposits on Mars have never been studied in-situ and this environment presents a new frontier for space exploration.

The "Mars Ice Access" mission is a key mission concept block within the notional strategy roadmap of the E3P programme (Fig.4.6).

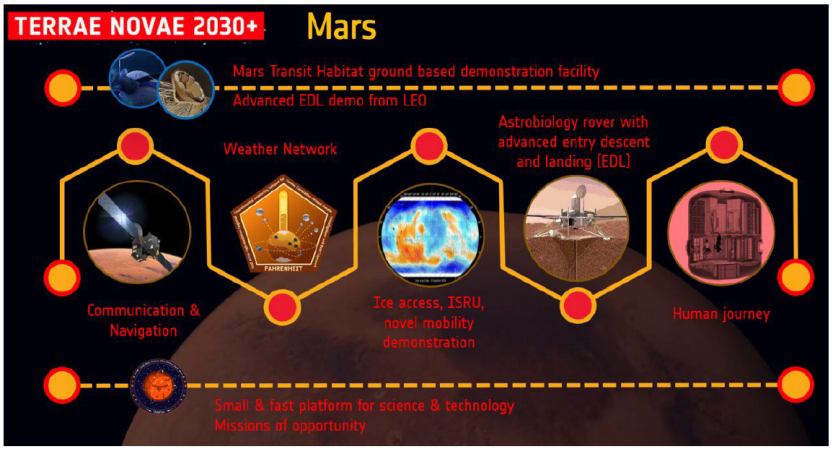


Figure 4.6: Terrae Novae 2030+ notional strategy roadmap for Mars [9]

In order to perform the future HRE Mars programming planning, the TEC-SYS was requested by ExPeRT to perform a full CDF study payload options for a novel "Mars Ice Access" mission for the 2030's. The mission objective would be to close the knowledge gaps for human mission planning related to reconnaissance of Mars resources, to investigate the astrobiological potential subsurface of ice environments, and to develop European ISRU capabilities. The study was funded by the DPTD Programme.

The study name is ARMADILLO: Accessing Resources on MArs, Drilling Ice and Looking for Life and Organics (logo in Fig.4.7).

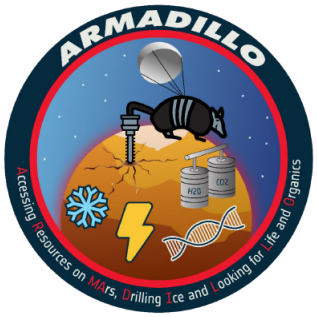


Figure 4.7: ARMADILLO study logo [9]

ARMADILLO Requirement

Among the ISRU enabling objectives, it was identified the demonstration of propellants production. Liquid Oxygen/Methane (LOX-CH4) based propulsion systems are currently regarded as the likely basis for crew ascent/return in future human mission planning. Both oxygen (O2) and methane (CH4) can be produced from Mars indigenous resources; the carbon dioxide present in the atmosphere can provide oxygen and carbon, while the subsurface water-ice can provide oxygen and hydrogen.

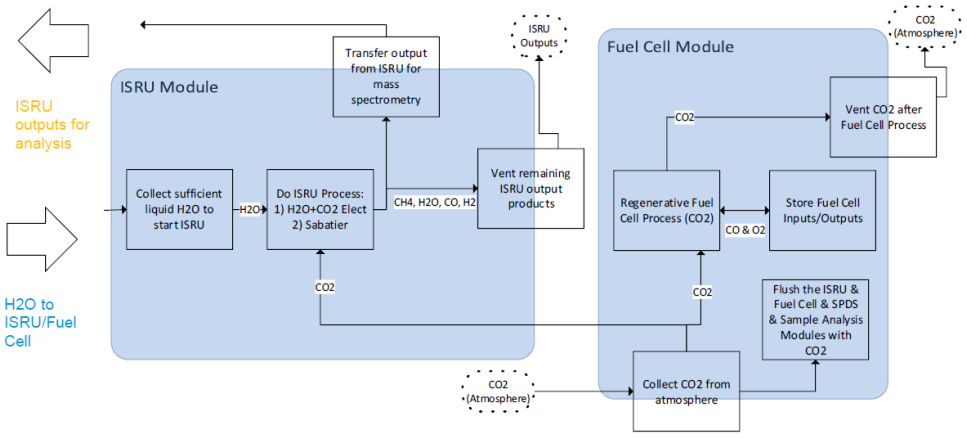


Figure 4.8: ARMADILLO Concept of Operations [9]

The diagrams in Fig.4.8 depict the overall potential concept of operations for the utilisation of martian indigenous resources (water-ice/regolith, CO2 atmosphere) within the ISRU demonstration chain.

Starting from the mission needs, in the *Exploration Mission-Pull Technology Requirements*

for the Technology Development Element (TDE) Workplan 2023 ExPeRT formulated the *ARMADILLO-8-1* Mission Pull requirement. The requirement reference and title fiche is shown in Tab.4.2 (for the full fiche refer to [9]).

TRQ Reference:	ARMADILLO-8-1
Title:	Development of a co-electrolyser for Oxygen and Syngas production

Table 4.2: ARMADILLO-8-1 TRQ Fiche

Once the requirement is formulated, from the Work Plan the fiche it is imported in the *Pull TRQ Public* requirements document, and the content of the requirements is loaded in TMT Part 2 in *Pull TRQ Requirements* Tab 4.9 from the *Update Database From Folder* button.

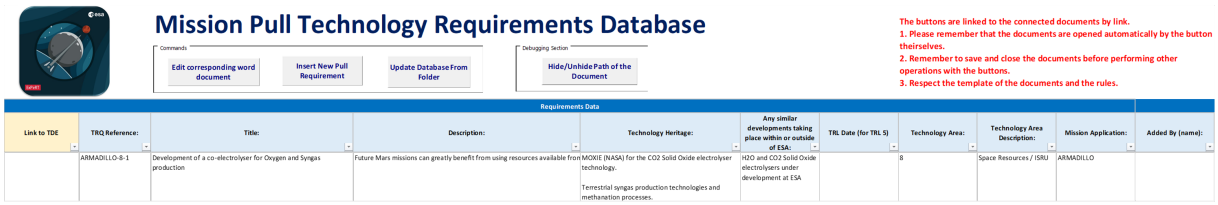


Figure 4.9: ARMADILLO requirement in TMT

T303-801EP Technology Activity

From the *Exploration Mission-Pull Technology Requirements* defined by ExPeRT, D/TEC proceeded with the formulation and proposal of the technology activity *T303-801EP* in collaboration with TECNET-EXP. Part of the fiche containing the data required at the purpose of the thesis is shown in Fig.4.3. The technology activity takes part in the *ESA-TDE-TECT-WP-2023-000005* 2023/2024 TDE Work-Procurement Plan [13].

TDE Activity Fiche					
Title:	Co-Electrolysis and Methanation for the Production of CH4 and O2 in Exploration Missions				
Reference	T303-801	**Budget**	650k€	**Duration**	24 Months

Table 4.3: T303-801 Technology Activity

Following the same logic as for the requirement, the activity fiche is included in the *TDE Work Procurement Plans* document and subsequently imported in *TDE Work-Procurement Plan* in Tab.4.10.

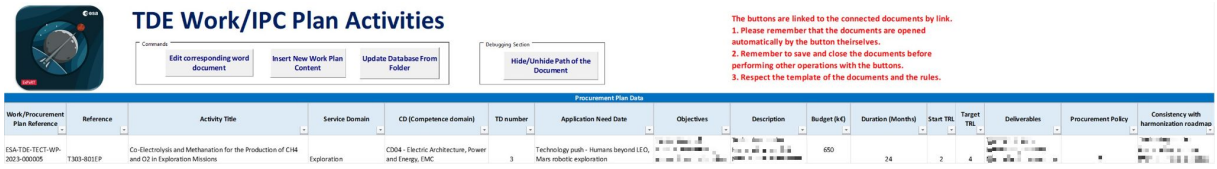


Figure 4.10: T303-801 in TMT

Once the activity has been included in TMT, the *Link to TDE* field in Fig.4.9 contains the activity reference *T303-801*, so that the activity can be linked to the requirement.

Once the activity is loaded in the *TDE Work-Procurement Plan* tab in TMT Part 2, it is fetched in the Exploration Database as a new activity simply updating it. Being a TEC activity, it is reported in TEC Actis2 tool, therefore also the Actis2 data source will include the same activity data in TMT.

4.2. Update to the 2020 ISRU Roadmap Campaign

Part of the tasks entrusted by ExPeRT is also related to the public outreach of the results, and once the activities are fetched in the Exploration Database they take part in the "knowledge bank", constituting the source of the published results.

4.2.1. 2020 ISRU Technology Areas

In September 2020 ExPeRT published the *In-Situ Resource Utilisation (ISRU) Campaign Roadmap* [7], containing a general overview of system and technology activities at ESA related to space resources and its potential utilisation. With the purpose of categorizing the technologies within the ISRU area, the chosen Roadmap logic is introduced hereafter.

In the attempt of creating a universal framework for Space Resource Utilisation, ESA and academia published the *A universal framework for Space Resource Utilisation* [28]. According to the paper, the ISRU value chain can be enclosed in a three-stage process flowsheet: Excavation, Beneficiation and Extraction. All these three steps (see Fig.4.11) need to be considered concurrently for a successful implementation of space resources utilisation.

As different technology areas are embedded in the steps of the ISRU chain, at the purpose of the roadmapping a different categorization was selected:

- Sampling, Transfer, Analysis;
- Excavation, Handling, Sorting;

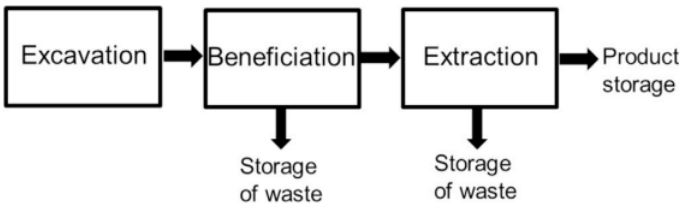


Figure 4.11: Universal flowsheet for SRU processes [28]

- Extraction, Processing, Storage;
- Manufacturing, Construction;
- Propulsion, Thermal, Power;
- Environmental Effects;
- Reuse, Recycle.

The defined categories are then used in the Roadmap Campaign in order to break-down the R&D activities, providing technology lists and roadmaps consistent with the ISRU chain steps.

The ESA ISRU-related activities not only include technology activities, but they also range from concept studies to system studies, and culminate with project level space missions; the Roadmap is including all these applications. The 2020 ISRU Campaign breakdown the technology activities according to Fig.4.12.

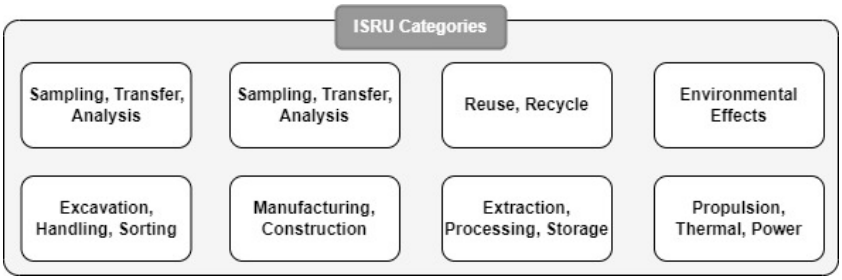


Figure 4.12: 2020 ISRU Roadmaps functionalities breakdown

The ISRU-related technology activities are categorized according to the defined steps of the ISRU chain (dashed boxes in the figure). In the published data the activities also include the *Application* column, which refers to the applicability context for each of the activities.

4.2.2. 2023 ISRU Technology Areas

The last version of the In-Situ Resource Utilisation (ISRU) Campaign Roadmap by ExPeRT dates back to 2020.
The new version drawn up in 2023 will represent its update, providing a new structure, new activities included from the workplans approved in the three years' time span and a new categorization of the technologies.
The proposed new categorization is the result of an analysis developed in the context of the *In-Situ Resource Utilization Gap Assessment Report* by the International Space Exploration Coordination Group (ISECG) [24]; the breakdown of the European ISRU roadmap according to the Global Roadmap allows a better interface with the global exploration scenario, resulting in a direct mapping of the ESA technologies against the identified ISRU sub-areas.

According to the ISRU report by the ISECG, the ISRU overall architecture can be schematized by Fig.4.13.

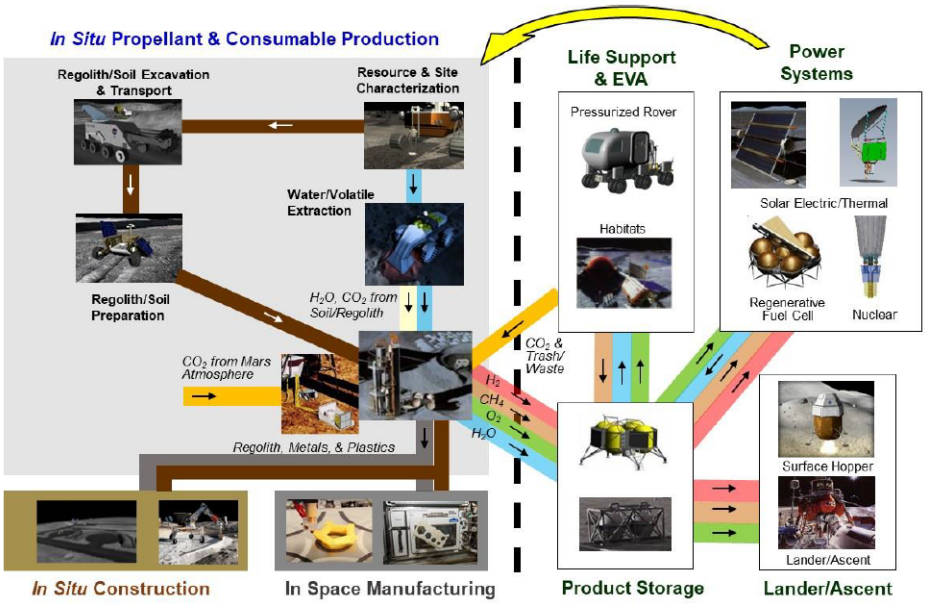


Figure 4.13: In-Situ Resource Utilization (ISRU) and Connections to Surface Systems [24]

The architecture embeds the three main ISRU areas depicted in the left-hand side of the chart (In-Situ Propellant & Consumable Production, In-Situ Construction, In-Space Manufacturing with ISRU-Derived Feedstock) and the right-hand side, containing all the interfaces required to support the overall architecture, included the manned interface.
Further breaking down the three main ISRU areas one by one allows to obtain the global

overview and functions of the architecture:

1. In-Situ Propellant and Consumable Production (ISPCP): it involves systems and capabilities that can harness and utilize resources found at the site of exploration for the production of propellants and mission consumables. There are four main sub-functional areas for ISPCP:
   1.1. Destination Reconnaissance and Resource Assessment;
   1.2. Resource Acquisition Isolation, and Preparation;
   1.3. Resource Processing for Production of Mission Consumables;
   1.4. Resource Processing for Production of Manufacturing and Construction Feedstock Materials.
2. In-Situ Construction: this involves activities such as site assessment and planning, area clearing and levelling, surface compaction and stabilization, berm building, and construction via sintering, moulds, bricks/slabs, and/or additive manufacturing.
3. In-Space Manufacturing with ISRU-Derived Feedstock: involves the creation of feedstock from local resources and the modification of equipment, to utilize these feedstocks for the production of individual parts, the assembly of more complex hardware or the repair and maintenance of assets. ISM involves manufacturing techniques (additive, subtractive, and near-net-shape forming), non-destructive evaluation, joining, repair, and assembly.

In the framework of updating the ISRU roadmap, the main interests is represented by the effective capabilities connected with the surface applications and functionalities, therefore the “Destination Reconnaissance and Resource Assessment” sub-functionalities is not included given its possible applicability to different areas, and its wide range of applications.

By grouping the functions of the architecture, the "In-Situ Material Exploitation" function has been introduced, conceived as the second part of the functionalities, embedding the exploitation of the extracted resources from the propellant and consumable production. The ISRU flowchart is then updated in Fig.4.14.

Beside the main ISRU areas, different capabilities and functionalities are required in order to support the overall architecture and infrastructure. The ISECG report [24] refers to these as “crosscutting challenges”: in order to enable future ISRU missions and to perform all identified operations, robust and reliable systems are needed, capable of withstanding the demanding lunar environment. Considering this, different challenges, relevant for multiple aspects and mission destinations, have been identified and analysed in the report:

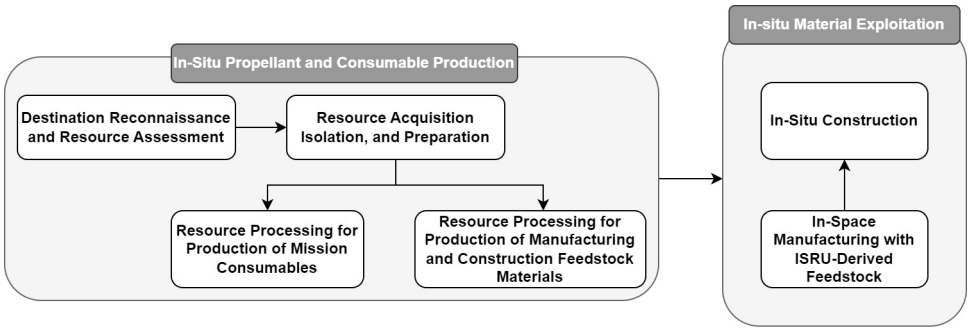


Figure 4.14: ISRU Flowchart

1. Power generation and storage;
2. Dust mitigation;
3. Modularity/Standardization of Hardware (recovery, disassembling, and reuse);
4. Cryogenic fluid production, management and transfer;
5. Habitation and Life Support systems;
6. Surface mobility and trafficability.

For the purpose of roadmapping the ISRU technologies mall changes have been applied to the actual Gap Assessment Report categorization. Firstly it has been decided to discard the technologies related to life support purposes as they cover a wide spectrum of technology areas, overlapping with other potential areas. Then, the "Modularity/Standardization of Hardware (recovery, disassembling, and reuse)" category has been renamed "Recovery Disassembling and Reuse", as to not only address hardware recycling, but also other materials and functionalities. Finally, a new category has been introduced and conceived as cross-cutting: the ISRU plant and studies are supporting the manned refuelling mission, and for this reason the "Propulsion Systems and Refueling" category is introduced.

Merging now the main ISRU functionalities and the crosscutting challenges the scheme in Fig.4.15 provides the high level overview of the new logic.

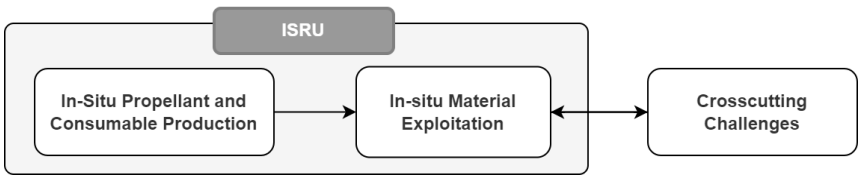


Figure 4.15: High level ISRU and related main functionalities

The further breakdown of Fig.4.15 provides the categorization chosen for the 2023 ISRU

Roadmap. The detailed breakdown chosen for the updated roadmap is shown in Fig.4.16 and it is consistent with the ISECG Report.

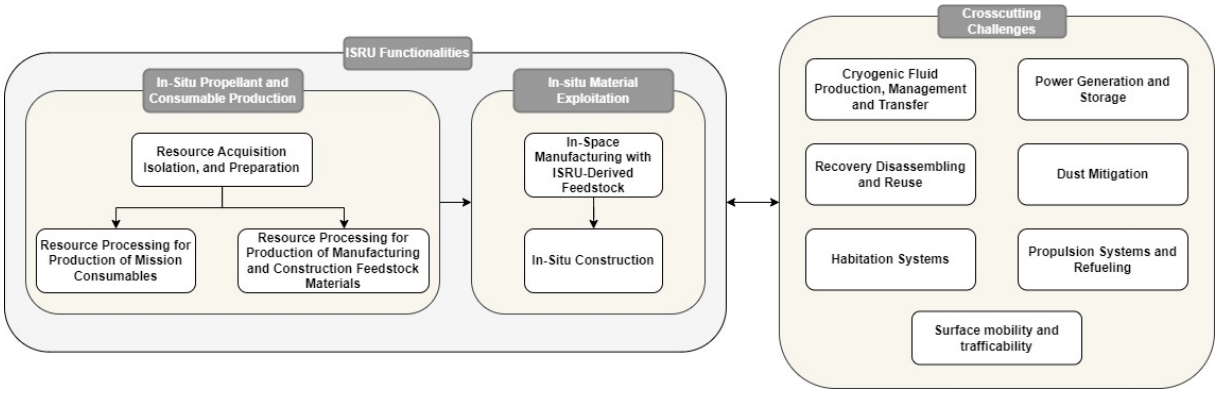


Figure 4.16: Proposed categorization for the 2023 ISRU Roadmap

Following the scheme, the proposed categorization will therefore produce a document where the Technology Activities part will be broken down in three tables, one for each main ISRU functionality (cyan boxes), each of them decomposed in sub-functionalities (white boxes).

4.3. TMT Part 3

Once the Exploration Database has been initialized, its content represents the list of technology activities from which ESA can drawn from for the further analysis or public outreach of material. In the case of the specific ISRU analysis, the activities are then categorized according to the chosen functionalities. With the purpose of supporting the technology analysis and breakdown, the idea of TMT Part 3 came to life.

The ISRU-related technology activities contained in the Exploration Technology Database are used as example to introduce the idea of TMT Part 3, with the final goal of generating the update of the 2020 ISRU Roadmap. All the technologies presented in the following Sections belong to the 2020 ISRU Roadmap Campaign [7], therefore the presented results are not the exhaustive list of technologies which will part in the 2023 ISRU Capaign Roadmap (needless to say that the logic and process will be exactly the same).[1]

[1]As the activities shown in the roadmap belong to the 2020 Roadmap, the data shown are still the "old" onces, in fact the KO, status and implementation dates are not updated in the roadmap.

4.3.1. Data and categorization storage

The usual steps involved in the technology-specific analysis of the Exploration Database are the following:

1. filtering;
2. export;
3. editing or adding of new entries;
4. publication.

Apart from the filtering action which can be manually operated by the database filters itself, once the user performs the export of the activities from the database he/she needs to make sure that the database at the moment of the export doesn't require status update, and most importantly that newly approved activities are not going to be present in the immediate future.
The funding idea of TMT Part 3 is to define a new database, namely used as a data storage, which represent the copy of the Exploration Database but with memory storage on the previously chosen categorizations.
The characteristic of this storage structure is that the data are fetched in from the Exploration Database itself, therefore in any moment can be updated. *TMT Part 3* logical architecture is shown in Fig.4.17.

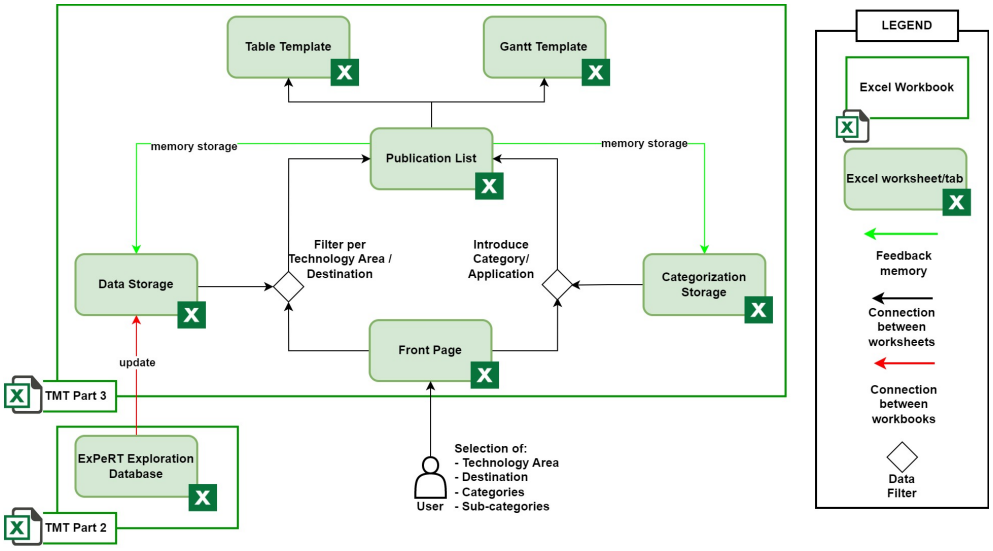


Figure 4.17: *TMT Part 3* logical architecture

The *Data Storage* tab represents the Exploration Database, but within the TMT Part 3 workbook. The screenshot of the tab is provided in Fig.4.18. Two are the main sections

present; the first one is the data import from *TMT Part 2*, representing the Exploration Database itself, and the other is the categorization and assigned sub-categorization memory.

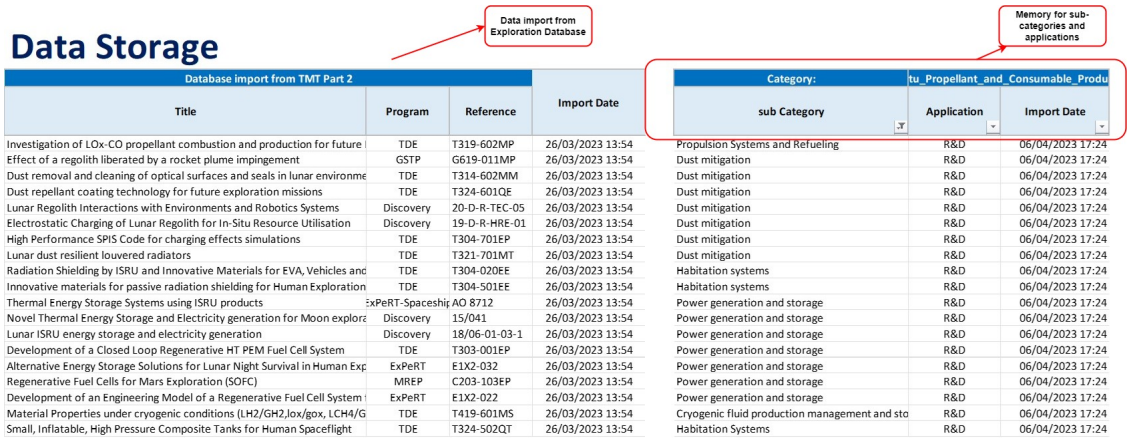


Figure 4.18: *Data Storage* interface

Once the activities are imported within *TMT Part 3*, the need is to categorize them. In the operation of filtering and/or categorization a found need is the one of memorizing the previously assigned categorizations. In fact in case the user wants to work on multiple roadmaps, or simply to keep in storage the previously assigned ones, the functionality would be in turn really useful.
In order to add the functionality of memory storage to TMT, the *Categorization Storage* tab is introduced in Fig.4.19: the defined categories in Fig.4.16 are here present.

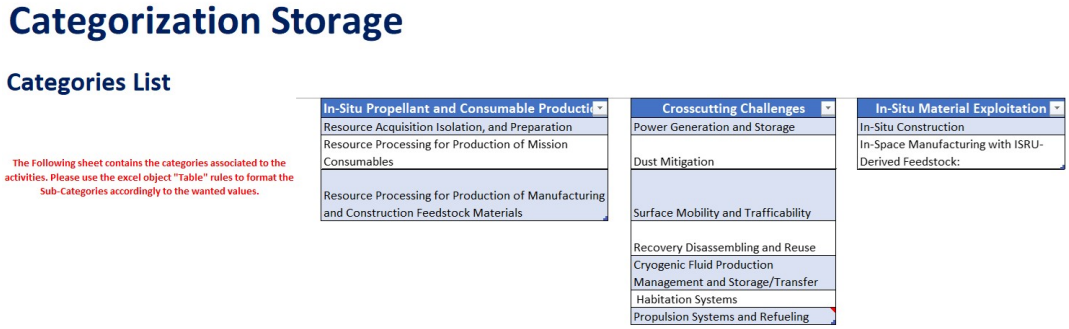


Figure 4.19: *Categorization Storage* tab and the ISRU functionalities

The tab is including all the previously assigned categories and relative sub-categories, representing the memory list of TMT. Once the categories are defined in this tab, the user can save the assigned categorization and the table in Fig.4.18 preserves the corresponding previously assigned.

4.3.2. Publication list and front page

The need of drafting the activities is then emerging, and the *Publication List* tab is created at this purpose (see the examples in Fig.4.21). The idea is to include in the list for publication only the filtered activities, and use that as a completely draftable list, in which the user can perform any kind of edit without modifying the Data Storage. The list is including the categorization, sub-categorization and application assigned to each activity, together with the K0 date of the associated contract. The user commands are used to perform the operations, such as clear or save of the current categorization, and same for the actual list imported in the tab.

All the operations to be performed are commanded by the TMT Part 3 *Front Page* worksheet in Fig.4.20.

From the *Data import for publication* button the activities can be selected either for Destination of per Technology Area and they are imported from the *Data Storage* to the *Publication List*. Then the category can be newly defined (by the *Create New Category*) or import the previously one existing (*Import Stored Category*).

Once the filtered activities have been included in the tab and the categorization and sub-categorization have been chosen and assigned, the tool is automatically generating a Table and a Roadmap for publication, accordingly to the given breakdown of the activities.
The templates are in fact stored in the *Table Template* and *Gantt Template* tab, which are iteratively including the sub-categorized activities. The generation of the tables and gantt containing the filtered data according to the chosen categorization represents the last functionality of TMT, in fact the public outreach is the last step in the whole lifechart.

4.4. The updated European ISRU Technology Roadmap

The updated version of the 2020 European ISRU Technology Roadmap is addressed in this chapter.

From the Exploration Database the activities ISRU-related are selected: the fastest way to perform this operations is represented by the filter per Technology Area.
The technology areas which are mainly addressing ISRU technologies and connected features are:

- 6. In-Situ Manufacturing, being one of the ISRU functionalities;
- 8. Space Resources Utilisation, represents the core of ISRU;

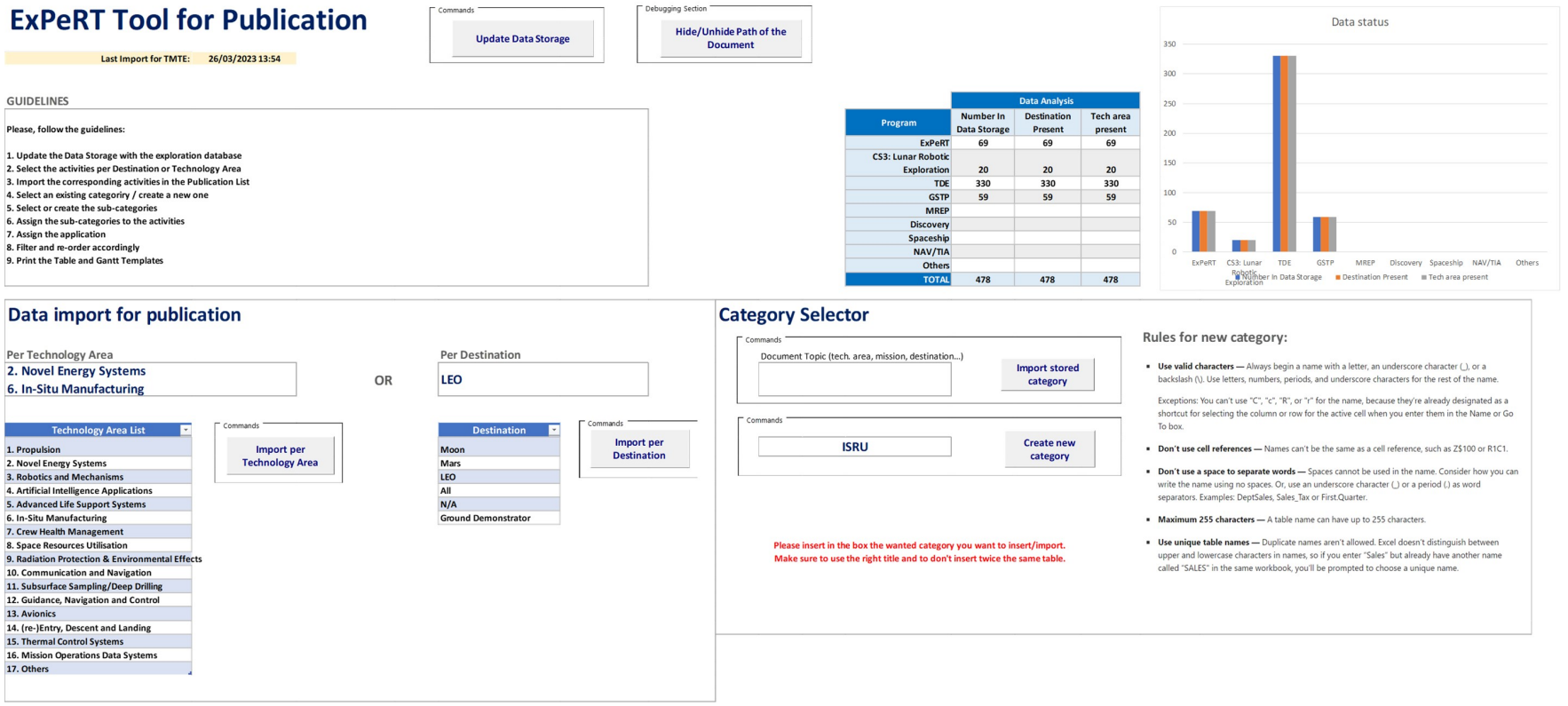


Figure 4.20: *Front Page* interface

Given the cross-cutting area of technologies, other technology areas are required for the side-functionalities: "Radiation Protection & Environmental Effects" applied to the surface environment, "Novel Energy Systems" given the fuel cells applications and research associated, "Robotics and Mechanisms" for mobility and actuator applications, "Propulsion" for refuelling interface, "Subsurface Sampling/Deep Drilling" for extraction and acquisition, "Thermal Control Systems" for survivability and finally "Advanced Life Support Systems" specifically applied to the reusability functionalities. Applying the automatic filter to the *Data Storage* list the *Publication List* is populated accordingly. Now, focusing on the publication list, this will include all the activities belonging to the chosen technologies area.

However, not all of them are part of the ISRU roadmap, in fact only part are selected, while the others are discarded. Moreover, this is not the full complete list, in fact activities from other departments or Planned for the next year are manually inserted. Once the activity list is fully ready, the categorization, sub-categorization and application is assigned in the *Publication Window*.

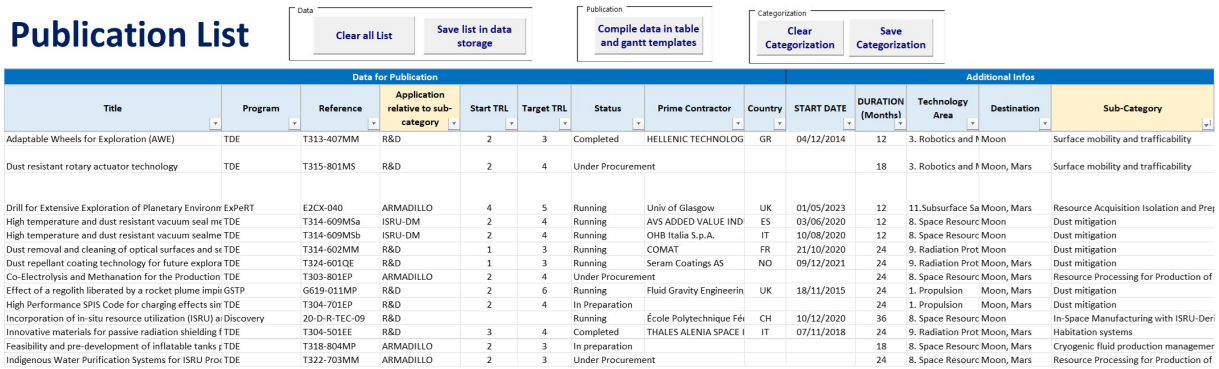


Figure 4.21: Technology area selection for ISRU technologies

There are mainly 2 outputs that are presented and can be produced by TMT: the first one are the roadmaps based on the ISRU functionalities, while the second are the roadmaps broken down per application.

Reconsidering the ARMADILLO example, the *ARMADILLO* application category is introduced, and the roadmaps are subdivded accordingly. Same holds for the *ISRU-DM* and *PROSPECT* applications. All the others activities belong to the R&D area.
The roadmaps per ISRU functionalities are subdivided accordingly with the new categorization chosen in Fig.4.16. Each of the Sub-sections below presents one of the main functionalities identified. The updates ISRU Roadmap contains 113 activities, against the 65 present in the 2020 version [7].

4.4.1. "In-Situ Propellant and Consumables Production" Roadmaps

This first main functionality is subdivided into other 3 sub-areas.

Resource Acquisition Isolation, and Preparation

Once a resource has been identified, located, and characterized, the next step in the ISRU chain is the ability to extract/acquire, separate, and potentially prepare the gas or material for processing.
The activities belonging to Tab.4.22 and Fig.4.23 highlight the ESA effort toward closing the gap. Both ARMADILLO and PROSPECT activities address these functionalities, in fact one of the main ARMADILLO objective is the resource acquisition [9].

Title	Program	Reference	Application	Start TRL	Target TRL	Status	Contractor/ Academic	Country
Resource Acquisition Isolation and Preparation								
Drill for Extensive Exploration of Planetary Environments by Robot (DEEPER) Extended Testing	ExPeRT	E2CX-040	ARMADILLO	4	5	Running	Univ of Glasgow	UK
Drill for Extensive Exploration of Planetary Environments by Robots (DEEPER)	TDE	T313-601MM	ARMADILLO	2	4	Completed	Univ of Glasgow	UK
Lunar Drill Development	GSTP	G619-002IL	PROSPECT	3	5	Completed	Selex Galileo	IT
Hammering Mechanism for ProsEED (PROSPECT Excavation and Extraction Drill)	GSTP	G613-029HS	PROSPECT	N/A	6	Completed	ASTRONIKA SP. Z O.O.	PL
ProSPA Improvement of Sample Containment for Volatile Analysis	TDE	T314-503MM	PROSPECT	2	5	Completed	Open University	UK
Development of In-situ regolith sampling Gear for GenerousExcavation of Regolith (DIGGER)	ExPeRT	E1X2-042	R&D	4	6	Running	CBK-PAN	PL
Instrumented Drill Development	SciSpacE	AO 10378	R&D	4	5	Under Procurement		
Development of In-situ regolith sampling Gear for Generous Excavation of Regolith (DIGGER) - Complement	ExPeRT	E2CX-034	R&D	3	5	Running	CBK-PAN	PL
Lunar Generic Regolith Acquisition/Sampling Paw (L- GRASP)	TDE	T313-002MM	R&D	1	3	Completed	Leonardo S.p.a.	IT
Step 5 of Prospecting Technologies Challenge: Technology maturation	ExPeRT	E2CX-036	R&D	N/A	N/A	Under Procurement		

Figure 4.22: European ISRU "Resource Acquisition Isolation, and Preparation" activities

Resource Processing for Production of Mission Consumables

The second step in the ISRU chain is the resource processing. It can be seen how a huge effort is put in the chemical processes based on ISRU products.
Considering again the ARMADILLO example, the activity *T303-801EP* is inserted in Tab.4.24, contributing to the knowledge bank in this ISRU area. The blanks in the gantt, allow to identify the activities which undergoing Procurement, in fact in the future more activities will be roadmapped.

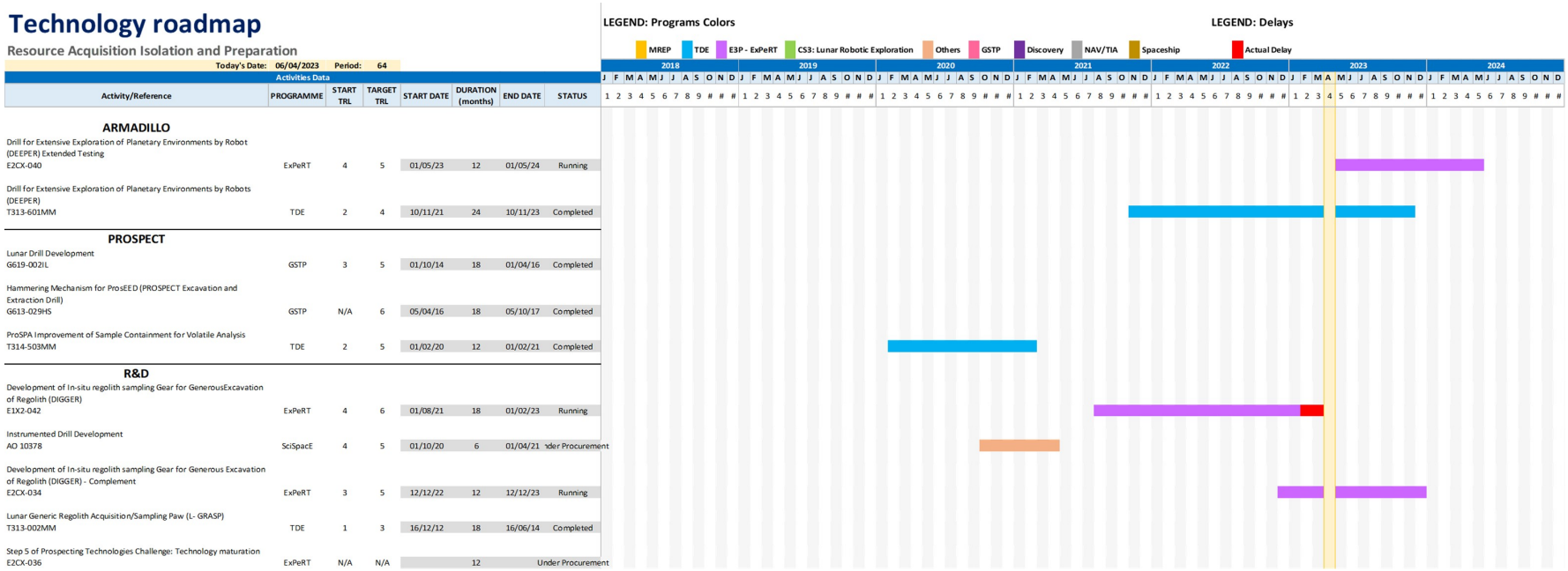


Figure 4.23: European ISRU "Resource Acquisition Isolation, and Preparation" roadmap

Title	Program	Reference	Application	Start TRL	Target TRL	Status	Contractor/Academic	Country
Resource Processing for Production of Mission Consumables								
Co-Electrolysis and Methanation for the Production of CH4 and O2 in Exploration Missions	TDE	T303-801EP	ARMADILLO	2	4	Under Procurement		
Indigenous Water Purification Systems for ISRU Processes	TDE	T322-703MM	ARMADILLO	2	3	Under Procurement		
The Metalysis FFC (Molten-salt electrolysis) process de-risk for extra-terrestrial oxygen production from ISRU	GSTP	G617-241TAcy	ISRU-DM	2	3	Completed	Metalysis	UK
ISRU-DM payload technology developments (acquisition, preparation, processing, analysis)	CS3	E2C3-028	ISRU-DM	3-4	5	Under Procurement	TAS	UK
High pressure water electrolyser development for exploration surface missions	TDE	T322-602EP	R&D	2	3	Completed	PROTOTECH A.S.	NO
ISRU System Demonstrator	ExPeRT	E1X2-016	R&D	3	4	Completed	SAS	BE
ISRU System Demonstrator	ExPeRT	E1X2-016-B	R&D	3	4	Completed	SAS	BE
Mars-atmosphere Breathing Electric Propulsion Thruster	TDE	T319-701MP	R&D	2	3	In Preparation		
System Development for an Innovative Regolith Excavation and Beneficiation Device in Support of Lunar In-situ Resource Utilisation (ISRU)	Discovery	19-D-R-TEC-07	R&D			Running	University of Manchester	UK
Versatile Energy, Water, Hydrogen and Oxygen production and Storage System based on areversible Photo-Electrochemical device	TDE	T722-601MM	R&D	1	2	Completed	ALMATECH SA	CH
ISRU Ground Based Research - Investment and Utilisation(FFC molten-salt elecrolysis Ground Demonstrator, Oxygen Purification and Process Development)	CS3	E2C3-002	R&D	3	4	Running		
Novel Plasma processing of Regolith	Spaceship	N/A	R&D	1	3	Completed	Academic (SS-EAC)	-
ROAST - Regolith Pyrolosis Experiment	Spaceship	N/A	R&D	3	4	Completed	Academic (SS-EAC)	-
Regenerative Ionic Liquids for O2 Production	Spaceship	N/A	R&D	1	3	Completed	Academic (SS-EAC)	-
Hydrogen Plasma reduction of Lunar Soil	Spaceship	N/A	R&D	1	3	Completed	Academic (Dutch Institute Fundamental Energy Research)	NL
Lunar Polar Simulant Design for Water Extraction	Spaceship	N/A	R&D	1	3	Completed	Academic (SS-ECSAT)	-
Electrochemical splitting of CO2 for carbon and oxygen production in Mars conditions	Discovery	21-D-R-TEC-06	R&D			Running	National Institute of Chemical Physics and Biophysics	EE
From Reactive Oxygen Detection to Oxygen Farming	Discovery	ETD 2021-05-b	R&D			Running	National Technical University of Athens	GR
ISRU on Mars: Plasma conversion of CO2 from the Martian atmosphere	Discovery	EISI_I-2021-03399	R&D			Running	Instituto Superior Tecnico	PT
ISRU Regolith to Oxygen conversion (ROXY) process investigation	ExPeRT	E2CX-042	R&D	N/A	N/A	In Preparation	Airbus DS	DE

Figure 4.24: European ISRU "Resource Processing for Production of Mission Consumables" activities

Resource Processing for Production of Manufacturing and Construction Feedstock Materials

The last step of the "In-Situ Propellant and Consumables Production" chain is the production of manufacturing and feedstock: it involves the production of feedstock that can be subsequently utilized for manufacturing and construction capabilities.

It can be seen how the lowest TRL, together with the high presence of Academia show that efforts must be put into these functionalities: in the current roadmap only one ac-

Technology roadmap

Resource Processing for Production of Mission Consumables

Today's Date: 06/04/2023 Period: 64

Activities Data

Activity/Reference	PROGRAMME	START TRL	TARGET TRL	START DATE	DURATION (months)	END DATE	STATUS
ARMADILLO							
Co-Electrolysis and Methanation for the Production of CH4 and O2 in Exploration Missions T303-801EP	TDE	2	4		24		Under Procurement
Indigenous Water Purification Systems for ISRU Processes T322-703MM	TDE	2	3		24		Under Procurement
ISRU-DM							
The Metalysis FFC (Molten-salt electrolysis) process de-risk for extra-terrestrial oxygen production from ISRU G617-241TAcy	GSTP	2	3	01/06/20	11	01/05/21	Completed
ISRU-DM payload technology developments (acquisition, preparation, processing, analysis) E2C3-028	CS3	04-Mar	5		18		Under Procurement
R&D							
High pressure water electrolyser development for exploration surface missions T322-602EP	TDE	2	3	06/12/19	30	06/06/22	Completed
ISRU System Demonstrator E1X2-016	ExPeRT	3	4	09/11/18	24	09/11/20	Completed
ISRU System Demonstrator E1X2-016-B	ExPeRT	3	4				Completed
Mars-atmosphere Breathing Electric Propulsion Thruster T319-701MP	TDE	2	3		24		In Preparation
System Development for an Innovative Regolith Excavation and Beneficiation Device in Support of Lunar In-situ Resource Utilisation (ISRU) 19-D-R-TEC-07	Discovery			05/03/20	30	05/09/22	Running
Versatile Energy, Water, Hydrogen and Oxygen production and Storage System based on areversible Photo-Electrochemical device T722-601MM	TDE	1	2	11/10/19	12	11/10/20	Completed
ISRU Ground Based Research - Investment and Utilisation(FFC molten-salt elecrolysis Ground Demonstrator, Oxygen Purification and Process Development) E2C3-002	CS3	3	4	01/12/20	24	01/12/22	Running
Novel Plasma processing of Regolith N/A	Spaceship	1	3	01/01/19	37	01/02/22	Completed
ROAST - Regolith Pyrolosis Experiment N/A	Spaceship	3	4	01/11/19	25	01/12/21	Completed
Regenerative Ionic Liquids for O2 Production N/A	Spaceship	1	3	01/01/20	12	01/01/21	Completed
Hydrogen Plasma reduction of Lunar Soil N/A	Spaceship	1	3	15/06/20	7	15/01/21	Completed
Lunar Polar Simulant Design for Water Extraction N/A	Spaceship	1	3	01/01/20	7	01/08/20	Completed
Electrochemical splitting of CO2 for carbon and oxygen production in Mars conditions 21-D-R-TEC-06	Discovery			28/05/21	24	28/05/23	Running
From Reactive Oxygen Detection to Oxygen Farming ETD 2021-05-b	Discovery			16/11/21	18	16/05/23	Running
ISRU on Mars: Plasma conversion of CO2 from the Martian atmosphere EISI_I-2021-03399	Discovery			18/11/21	12	18/11/22	Running
ISRU Regolith to Oxygen conversion (ROXY) process investigation E2CX-042	ExPeRT	N/A	N/A	01/05/23	4	01/09/23	In Preparation

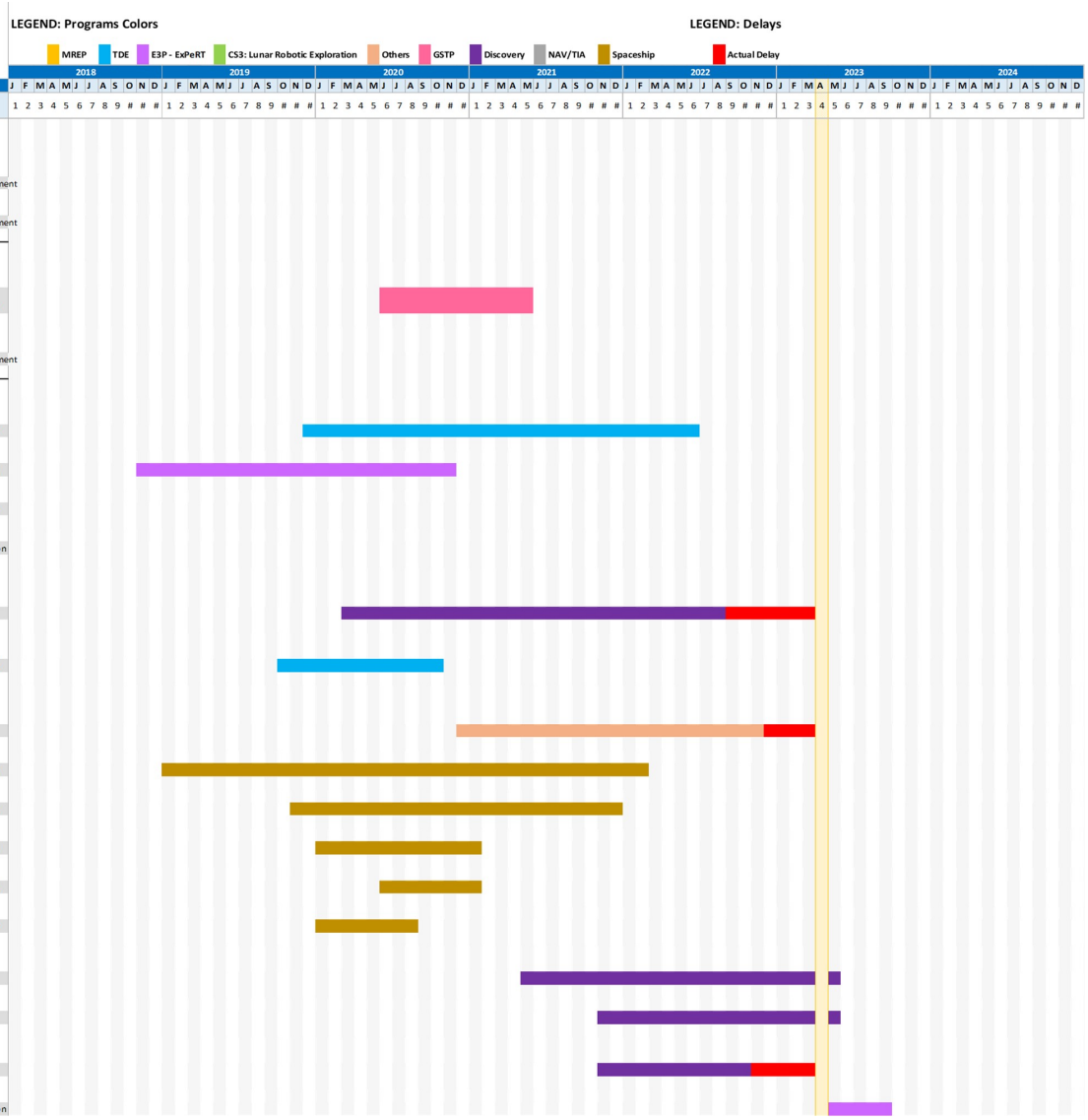


Figure 4.25: European ISRU "Resource Processing for Production of Mission Consumables" roadmap

tivity results to be Under Procurement.
Thanks to the automatic delay calculation it is immediate to display delays in ongoing development for the Running activities, in fact the red flag provides an immediate view of the ongoing development status.

Title	Program	Reference	Application	Start TRL	Target TRL	Status	Contractor/ Academic	Country
Resource Processing for Production of Manufacturing and Construction Feedstock Materials								
Microwave heating of ISRU feedstock	TDE	T314-607MM	R&D	1	4	Running	RINA CONSULTING SPA	IT
Solar-assisted photosynthesis oxygen and fuel production	Discovery	AO 3-16745	R&D	1	3	Under Procurement	Academic	UK
Microwave Processing of Regolith	Spaceship	N/A	R&D	1	4	Completed	Academic (SS-EAC)	-
Sintering of Regolith simulant material	Spaceship	N/A	R&D	2	4	Completed	Academic (DLR & SS-EAC)	DE
(Ariadna) Basalt fibre reinforced geopolymer cement made from lunar regolith simulant	Discovery	18-9401	R&D	2	4	Completed	Academic (Østfold University College)	NO
(Ariadna) Additive manufacturing of functionally graded ceramics with in-situ resources	Discovery	19-9401	R&D	1	3	Completed	Academic (TU Delft)	NL
(Ariadna) Moon fibres	Discovery	19-D-A-05	R&D	1	3	Completed	Academic (RWTH Aachen University)	DE
Selective Laser Sintering of Regolith	Spaceship	N/A	R&D	2	3	Completed	Academic (SS-EAC)	-
Microwave Heating Apparatus Of Lunar Regolith For Variant Experiments Of Lunar ISRU Missions (MARVEL)	Discovery	20-D-T-TEC-03-b	R&D			Running	The Open University	UK
Producing inexpensive carbon-neutral steel from low-grade feedstock applying space In-Situ Resources Utilization paradigm	Discovery	EISI_I-2022-00572	R&D			Running	Maana Electric SA	LU
Reactor for production of heat and pure ISRU metal during lunar nights through thermite reaction	Discovery	ETD 2021-06	R&D			Running	MAANA Electric	LU

Figure 4.26: European ISRU "Resource Processing for Production of Manufacturing and Construction Feedstock Materials" activities

4.4.2. In-situ Material Exploitation

Once the resources have been processed and the ISRU feedstock has been produced the second main functionality involve in the full ISRU chain is the exploitation of the material. There mainly 2 sub-areas involved: the first covers the manufacturing, while the second address the construction and preparation of the ISRU site on the surface.

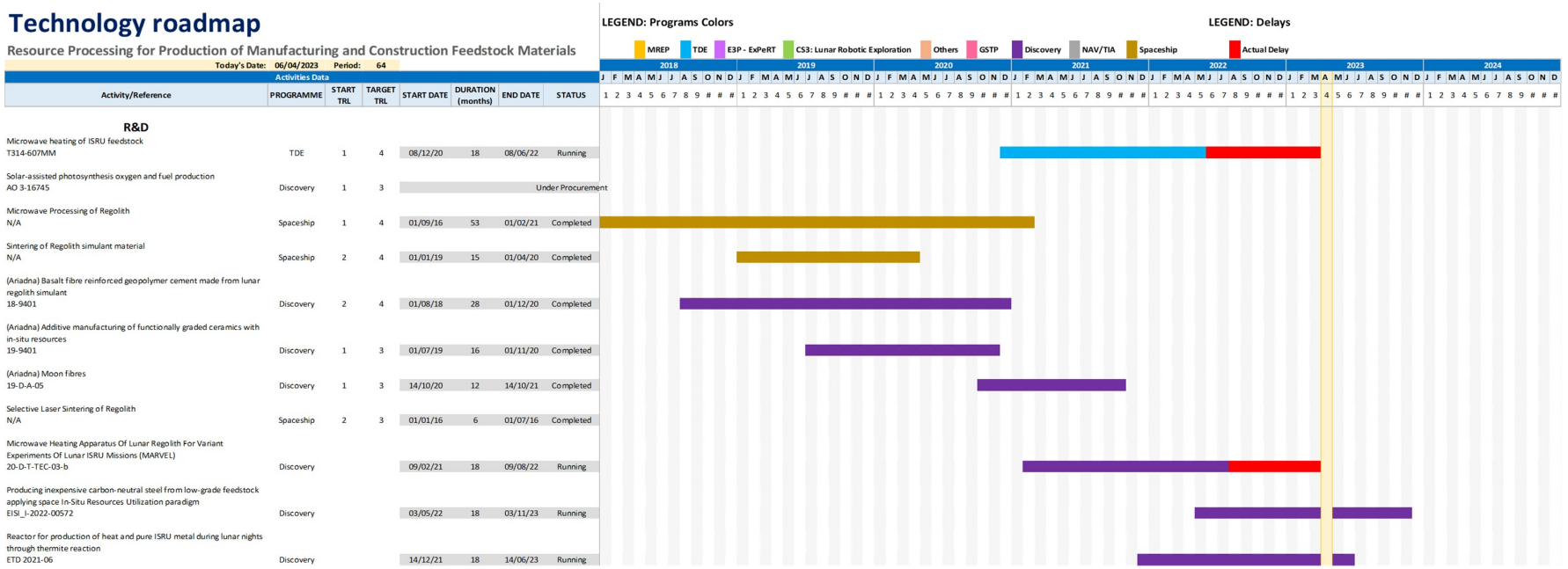


Figure 4.27: European ISRU "Resource Processing for Production of Manufacturing and Construction Feedstock Materials" roadmap

In-Space Manufacturing with ISRU-Derived Feedstock

The ability to manufacture and repair hardware is critical for long-duration human missions to minimize logistics and spares inventory/mass, and minimize mission risk from delayed replacement delivery due to the distance from Earth or transportation failures.
The In-Space Manufacturing activities covers the functionalities of elaborating the feedstock at this purpose.
Innovative additing manufacturing techniques and 3D printing technologies are under research, highlighting the efforts toward this emerging area. Activities coming from the Discovery programmes are mainly involved, and ExPeRT is not currently involved in this area.[2]

Title	Program	Reference	Application	Start TRL	Target TRL	Status	Contractor/Academic	Country
In-Space Manufacturing with ISRU-Derived Feedstock								
Incorporation of in-situ resource utilization (ISRU) and additive manufacturing (AM) for lunar exploration	Discovery	20-D-R-TEC-09	R&D			Running	École Polytechnique Fédérale de Lausanne (EPFL)	CH
Limited resources manufacturing technologies	TDE	T324-002QT	R&D	1	2	Completed	FOTEC Forschungs- und Technologietr	AT
Regolith Slurry Extrusion Printing	Spaceship	N/A	R&D	3	4	Completed	Academic (SS-EAC)	-
Aluminium Casting using Regolith Molds	Spaceship	N/A	R&D	1	3	Completed	Academic (SS-EAC)	-
A novel Lithography Metal Manufacturing (LMM) process to produce highly accurate parts from recycled powders from scrap metals on the Moon.	Discovery	20-D-T-TEC-03-d	R&D			Running	OHB	DE
Adaptation of Lithography - Based Ceramic Manufacturing (LCM) to process lunar regolith and optimization of the process steps for the Moon and reduced logistics	Discovery	20-D-S-TEC-03-f	R&D			Completed	OHB	DE
Advanced microcrystalline solar cell manufactured from lunar regolith	Discovery	20-D-R-TEC-29	R&D			Running	Tallinn University of technology	EE
CLOSING THE LOOP ON POLYMERS 3D PRINTING: 3D PRINTER USING THE FUSED FILAMENT FABRICATION (FFF) PROCESS ABLE TO PRODUCE PARTS IN VACUUM CONDITIONS USING RECYCLED FILAM	Discovery	20-D-T-TEC-03-i	R&D			Running	Azimut Space Gmbh	DE
Off-Earth manufacturing through self-growing 3D printer	Discovery	20-D-S-TEC-03-a	R&D			Running	University of Trieste	IT

Figure 4.28: European ISRU "In-Space Manufacturing with ISRU-Derived Feedstock " activities

In-Situ Construction

The last step of the ISRU chain is represented by the In-Situ Construction area.
In-Situ Construction involves activities such as site assessment and planning, area clearing and levelling, surface compaction and stabilization, berm building, and construction via sintering, moulds, bricks/slabs, and/or additive manufacturing. For the realization of sustainable exploration missions and ISRU infrastructure development, it is an important

[2]Activities may be in Planning status for future developments.

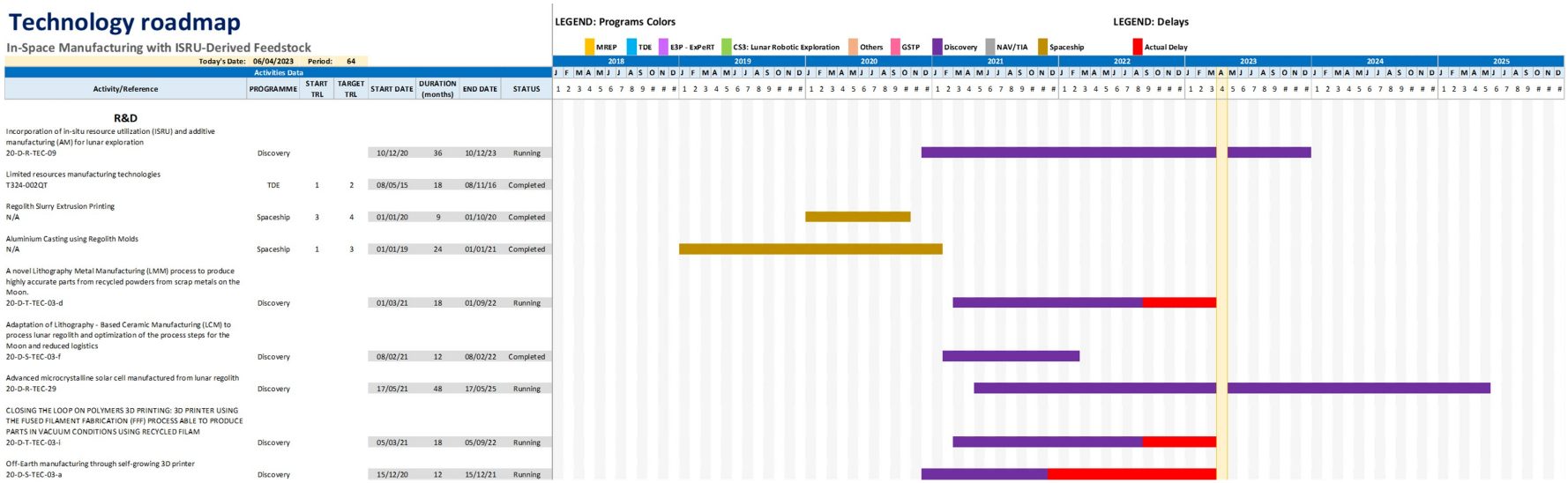


Figure 4.29: European ISRU "In-Space Manufacturing with ISRU-Derived Feedstock " roadmap

activity and covers the aforementioned range of activities.
Looking at Tab.4.30 and Fig.4.31 all the activities belong to the Discovery programme, in fact being in the last step of the chain the construction area is still under research, and through this programme ESA is collecting idea from all over Europe.

Title	Program	Reference	Application	Start TRL	Target TRL	Status	Contractor/Academic	Country
In-Situ Construction								
URBAN - Conceiving a lunar base using 3D printing technologies	Discovery	15/012	R&D	1	3	Completed	OHB	DE
3D Printed Building Blocks Using Lunar Soil	Discovery	GS 09/010	R&D	1	3	Completed	Alta	IT
3D printing of a model building block for a lunar base outer shell	GSTP	G617-153QT	R&D	3	5	Completed	DLR	DE
(Ariadna) Growing fungi structures in space	Discovery	16-6101	R&D	1	2	Completed	Academic (Utrecht University, Officina Corpuscoli)	NL
(Ariadna) Robotic manufacturing of fibrous structures in space	Discovery	17-9401	R&D	2	4	Completed	Academic (University of Stuttgart)	DE
COMBINING ISRU AND SPACE DEBRIS FOR CONSTRUCTIONS ON THE MOON	Discovery	20-D-R-HRE-02	R&D			Running	TECHN UNIV BERLIN	DE
Energy-efficient regolith compactor for surface construction	Discovery	20-D-T-TEC-03-I	R&D			Completed	Astronika	PL
Extraterrestrial Robotic Construction with Found Materials	Discovery	21-D-R-TEC-12	R&D			Running	ETH Zürich	CH
OFF-EARTH MANUFACTURING OF CROP-FRIENDLY LUNAR GREENHOUSES	Discovery	20-D-T-TEC-03-c	R&D			Running	NTNU SAMFUNNSFORSKNING A/S - CIRIS	NO
PAVING THE ROAD FOR LARGE AREA SINTERING OF REGOLITH	Discovery	20-D-T-TEC-03-h	R&D			Running	Bundesanstalt Fur Materialforschung Und -Prufung	DE
Selective Laser Melting (MSLM) for the Construction of Infrastructures on the Moon	Discovery	20-D-T-TEC-03-f	R&D			Running	Tech Univ Berlin	DE

Figure 4.30: European ISRU "In-Situ Construction" activities

4.4.3. Cross-cutting Challenges

The cross-cutting challenges covers the capabilities and functionalities that are required in order to support the overall architecture and infrastructure. As seven different areas were identified, the roadmaps present a variety of programmes and activities.
Being the ISRU the main focus of the analysis, the tables and roadmap associated to the cross-cutting challenges are presented in Appendix A.

Figure 4.31: European ISRU "In-Situ Construction" roadmap

5 | Conclusion and Future Work

The thesis investigated the idea of exporting the whole ExPeRT project management flowchart in the exploration domain within a platform, capable of interfacing with the current existing tools and methodologies, with the aim of monitoring and supporting the R&D activities life-cycle. This final chapter provides a summary of the achieved results and proposes the recommandations required to overcome the main issues met.

5.1. Summary of the Results

The research question of the thesis started with the presentation of the ExPeRT Technology Flowchart and the correlated request to optimize it. Given the hard constraints imposed and the amount of interfaces requires between different entities and stakeholders, the proposal of merging the cycle within one tool, developed as a shareable platform has been welcomed by the team.
The initial idea of supporting ExPeRT in its daily operations has been extended to the design and implementation of tool used for co-working, allowing the team to collaborate in a widely-known environment. More, TMT wants to highlight the need of the data standardization and coordination among the departments, in fact the ExPeRT environment has been merged in the Exploration Database at this purpose.
The physical existence of a database of such a kind wasn't previously addressed [1] and the easiness in the update capabilities allow to demonstrate how useful could be to adopt ad hoc platforms in the everyday work.

TMT and the Exploration Database idea have been presented to the team and welcomed, at the point that the tool is now working and operational in the ExPeRT Sharepoint, available for the team to be used and to be supportive to the R&D area for exploration. The initial purpose of showing and proposing ideas has evolved, in fact the user case on the ISRU technologies shows the effectiveness of the tool in the ExPeRT everyday life, at the purpose that the update of the European ISRU Roadmap has been produced thanks to TMT itself.

[1] At list for the ExPeRT interface with the other departments.

5.2. TMT limitations and proposals to ESA

Despite the platform is conceived to be user-friendly and usable from the whole team for the everyday operations, its intrinsic connections and standardization imply a careful and clean usage. Once TMT has been loaded on Sharepoint three training sessions have been done to the team in order to teach the users on how to use TMT and possibly to debug it when required.

Overcoming the initial request to bring ideas and to support them by means of working evidence, the platform is now is operational, but it is immediately clear how multiple functionalities and improvements can be adopted.

5.2.1. Limitations

There limitation related to TMT are mainly of two types: the first ones are correlated to the structure itself, while the second to the Excel functionalities and coding logic.

TMT wide structure and interconnections

Given the amount of data and the number of interconnections between the Excel worksheets and workbooks, a non-familiar user can be lost in the tool as it is difficult to translate each tab to its immediate functionality and linkage to the others. In fact being the tool consisting of more than 30 Excel worksheets (and often similar to each other) a proper training is required for a safe usage.
The initial idea of merging all the tool within one Workbook turned out to be not operationally efficient and not user-friendly, in fact one single Excel embedding more than 30 Worksheets requires more time to be navigated through than to opening other Workbooks.

The links between the objects represent also a hot spot, in fact in the operation of accessing one Object Excel perform the Opening command, therefore in case the Object is already open warnings, or breakpoints can occur; it is require to use TMT saving the document before performing the interconnection operations.

Finally, for what concerns the Word tables and import of the data within TMT, the automatic data fetching works only when the tables respect the given data format, in fact in case a non-watchful user loads the tables with the wrong format errors occur.

User interface limitations

Excel requires the user to declare the variables when performing operations in the cell contents, and this represents a criticality in case the data format is not always the same. There are countless errors and inconsistencies along the overall flowchart which require a manual debug given the data format not consistent with the one declared.
The *Inconsistencies* sections in TMT are in fact based on codes which expect the error, upon statistical analysis of the most common; different kind of errors or wrong data format are therefore to be further examined.

The Excel worksheet itself represent the user interface limitations. Even though all the information are easily contained in one Worksheet and categorized thanks to the embedded columns structure, most of the tab contain lots of data which are not properly displayed, and a manual stretch of the columns and rows is required to visualize them. The templates generated and coding developed ad hoc for what concerns the roadmaps, tables and pivot charts, can be further improved in terms of graphic and update speed; when hundreds of entries are present the editing of the cells color can take a consistent amount of time to be performed.

Further updates have to be performed in the user interface itself, also for what concerns the editing possibility; the idea of preventing Excel from editing in the unwanted cells can be implemented, and it would allow a safe usage, minimizing the risks to affect the data.

5.2.2. Proposal to ESA

Starting from the platform itself, Excel was the first solution identified given its wide usage, existing interfaces to the same tool, and the immediate possible implementation.
However there is a wide range of possibilities which can represent a TMT evolution or substitution in order to overcome the encountered limitations, in fact the idea of implementing TMT in "low code" logic, using VBA to interface it with other inputs and to exchange data, has been revealed to be successful, but limited in its capabilities and configurability.
Focusing on the solution proposal as a platform, there are mainly two possibilities for what concerns the platform logic: the traditional development or the low code/no code logic.

Off-the-shelf platforms

A small literature research has been performed in order to assess the best off-the-shelf applications used to tackle the problem, representing a possible alternative for the low code/no code logic.
According to [29], among the countless project management applications and platforms the following list have been considered as part of the trade-off conducted:

- Monday.com [54], widely used for project management, flexible and configurable, presents a variety of interfaces and layout to view the task;
- Trello [55], project management oriented but more focused on the Kanban project view;
- Asana [56], designed around tasks and subtasks arranged into different sections that can be assigned to either an individual or teams;
- Smartsheet [61], it's a spreadsheet software but lacks of essential collaboration and reporting features;
- Basecamp [58], presents chats, collaborative views, cloud storage combining several tools into one, specifically suited for "cliendside" user access;
- Airtable [59], can be easily integrated with other tools, more similar to an Excel Spreadsheet, allows the automation and generation of workflows in a configurable platform;
- Hive [60], flexible tool that offers its users time tracking, reporting capabilities, and multiple views to handle project management with ease.

Given the feature of workflows automation, the user-friendly view and data organized in spreadsheet, the numerous integration with pre-existing tools and collaboration, Airtable has been selected as a promising candidate, representing the most suitable off-the-shelf evolution of TMT.

Coding logic trade-off

Given the interfaces with the existing tools and capabilities within the agency, a traditional development would allow to make TMT 100% customizable and to make a unique user interface to be integrated within the ESA system.
On the other side the low code offers a faster implementation, adapting the needs to pre-existing tools and capabilities.

	Standard development	Low code/no code logic
Implementation time		X
Cost	X	
Configurability		X
Customization	X	
Safety and Privacy	X	
Maintainability	X	X

Table 5.1: TMT development logic trade-off

Considering pros and cons of both options the trade-off in Tab.5.1 is run, and overall the suggested idea is the one of interfacing the existing tools with an ad hoc platform, developed with traditional approach, capable of interconnecting with PRONTO and be operative within the ESA Sharepoint and system, being embedded in it.
The usage of off-the-shelf software and low code logic allows a faster and easier implementation, but at the purpose of creating a reliable and customized platform, capable of interfacing with different existing tools the standard coding is required.

In a hypothetical future Actis2, PRONTO, and all the other applications currently used by the different department for reporting and monitoring of the activities could be merged, or interfaced by means of an application following the idea of TMT.
This not only would allow to gain autonomy in the operation of global monitoring (ceasing the need of asking for updates), but could provide reliable overview, and would promote the idea of ESA working as one organ, breakdown in department but intrinsically interconnected.

5.3. Conclusion

Although the ExPeRT Technology Flowchart and the project management cycles involve interfaces between different stakeholders and tools, the funding idea of TMT and its mock-up version revealed the benefit of such a platform in the overall coordination and monitoring of the process.
The first version of TMT is operational and currently in use by ExPeRT, but an improved version of the platform is recommended to be implemented in the future.
The development of an ad hoc application requires time and investments, but as was the case for PRONTO, the platform revealed itself to be operationally efficient, reducing the global effort and promoting collaboration.

A | Appendix A: ISRU Roadmaps

Title	Program	Reference	Application	Start TRL	Target TRL	Status	Contractor/Academic	Country
Dust mitigation								
High temperature and dust resistant vacuum seal mechanisms	TDE	T314-609MSa	ISRU-DM	2	4	Running	AVS ADDED VALUE INDUSTRIAL ENGINEER	ES
High temperature and dust resistant vacuum sealmechanisms	TDE	T314-609MSb	ISRU-DM	2	4	Running	OHB Italia S.p.A.	IT
Dust removal and cleaning of optical surfaces and seals in lunar environments	TDE	T314-602MM	R&D	1	3	Running	COMAT	FR
Dust repellant coating technology for future exploration missions	TDE	T324-601QE	R&D	1	3	Running	Seram Coatings AS	NO
Effect of a regolith liberated by a rocket plume impingement	GSTP	G619-011MP	R&D	2	6	Running	Fluid Gravity Engineering Ltd	UK
High Performance SPIS Code for charging effects simulations	TDE	T304-701EP	R&D	2	4	In Preparation		
Lunar dust resilient louvered radiators	TDE	T321-701MT	R&D	1	3	Running	ESR TECHNOLOGY LTD	UK
Lunar Regolith Interactions with Environments and Robotics Systems	Discovery	20-D-R-TEC-05	R&D			Running	DLR	DE
Electrostatic Charging of Lunar Regolith for In-Situ Resource Utilisation	Discovery	19-D-R-HRE-01	R&D	1	3	Running	Academic (Imperial College London)	UK
Design and manufacturing of lunar dust simulant for hardware testing	Others	N/A	R&D	2	5	Completed	Academic (SACF-ECSAT)	-
Characterisation of dust and sample properties in lunar environment	TDE	T314-007MM	R&D	1	3	Completed	SITAEL S.P.A.	IT
Dust electrostatic charging, transport and contamination model for Lunar Lander and human exploration missions	TDE	T304-002EE	R&D	Algorithm	Prototype	Completed	ONERA	FR
Experimental Validation of regolith/surface probes interactions predictive tools for Exploration	TDE	T304-702EP	R&D	2	4	Under Procurement		
Innovative Material for Lunar Passive Dust Mitigation	Discovery	ETD 2021-07	R&D			Running	Italian Aerospace Research Centre - CIRA S.c.p.a.	IT
Lunar Environment Surface Package	TDE	T304-802EP	R&D	2	3	Under Procurement		
Modelling and Testing of Plume/Regolith Interaction on Lunar Landing Pads and Berms	TDE	T318-702MP	R&D	2	4	Running	TUD	DE

Figure A.1: European ISRU "Dust Mitigation" activities

Title	Program	Reference	Application	Start TRL	Target TRL	Status	Contractor/Academic	Country
Propulsion Systems and Refueling								
Investigation of LOX-CO propellant combustion and production for future Mars mission applications	TDE	T319-602MP	R&D	3	4	Under Procurement		
Modular Water Electrolysis Propulsion System (Chemical- Electrical)	TDE	T719-704MP	R&D	2	3	Running	URA Thrusters	UK
Prototyping of Spacecraft Re- fueling	TDE	T713-602MP	R&D	1	3	Running	TAS	FR
Mars-atmosphere Breathing Electric Propulsion Thruster	TDE	T319-701MP	R&D	2	3	In preparation		
Water propulsion system	TDE	T519-413MP	R&D	1	3	Completed	Omnidea-RTG	DE

Figure A.2: European ISRU "Propulsion Systems and Refueling" activities

Title	Program	Reference	Application	Start TRL	Target TRL	Status	Contractor/Academic	Country
Surface mobility and trafficability								
Adaptable Wheels for Exploration (AWE)	TDE	T313-407MM	R&D	2	3	Completed	HELLENIC TECHNOLOGY OF ROBOTICS SA	GR
Dust resistant rotary actuator technology	TDE	T315-801MS	R&D	2	4	Under Procurement		
Robust and (semi) Autonomous Platform for Increased Distances (RAPID)	TDE	T313-702MM	R&D	2	3	Running	GMV AEROSPACE AND DEFENCE, SA	ES
Rotary actuators in harsh environment	TDE	T315-001MS	R&D	2	3	Completed	Leonardo S.p.a.	IT

Figure A.3: European ISRU "Surface mobility and Trafficability" activities

Title	Program	Reference	Application	Start TRL	Target TRL	Status	Contractor/Academic	Country
Power generation and storage								
Development of Lightweight High Temperature Insulation for Regenerative Fuel Cell and In- Situ Resource Utilisation	TDE	T324-801MT	ARMADILLO	2	3	Under Procurement		
Development of a Closed Loop Regenerative HT PEM Fuel Cell System	TDE	T303-001EP	R&D	3	5	Completed	Advent Technologies	GR
Development of an Engineering Model of a Regenerative Fuel Cell System for PowerGeneration on Mars	ExPeRT	E1X2-022	R&D	4	5	Running	Prototech	NO
Thermal Energy Storage Systems using ISRU products	Spaceship	AO 8712	R&D	1	2	Completed	Academic (SS-EAC)	-
Novel Thermal Energy Storage and Electricity generation for Moon exploration	Discovery	15/041	R&D	1	2	Completed	Azimuth Space	DE
Lunar ISRU energy storage and electricity generation	Discovery	18/06-01-03-1	R&D	3	4	Completed	UPC	ES
Alternative Energy Storage Solutions for Lunar Night Survival in Human Exploration Scenarios (PEMFC)	ExPeRT	E1X2-032	R&D	3	5	Completed	Prototech	NO
Regenerative Fuel Cells for Mars Exploration (SOFC)	MREP	C203-103EP	R&D	3	4	Completed	Prototech	NO
Fuel cell applications for future missions	GSTP	GT17-431EP	R&D	3	4	Running	Energie Technologie GmbH	DE
ISRU proof unitized regenerative fuel cells	Discovery	21-D-R-HRE-02	R&D			Running	Graz University of Technology	AT

Figure A.4: European ISRU "Power Generation and Storage" activities

Title	Program	Reference	Application	Start TRL	Target TRL	Status	Contractor/Academic	Country
Cryogenic fluid production management and storage/transfer								
Feasibility and pre-development of inflatable tanks propellant storage	TDE	T318-804MP	ARMADILLO	2	3	In preparation		
In situ propellant liquefaction transfer and storage for Moon and Mars	TDE	T319-801MP	R&D	2	4	In preparation		
Material Properties under cryogenic conditions (LH2/GH2,lox/gox, LCH4/GCH4)	TDE	T419-601MS	R&D	1	3	Completed	ENERGIE TECHNOLOGIE GMBH	DE

Figure A.5: European ISRU "Cryogenic fluid production management and storage/transfer" activities

Title	Program	Reference	Application	Start TRL	Target TRL	Status	Contractor/Academic	Country
Habitation systems								
Innovative materials for passive radiation shielding for Human Exploration spaceflight	TDE	T304-501EE	Habitation systems	3	4	Completed	THALES ALENIA SPACE ITALIA SPA	IT
Radiation shielding by ISRU and/or innovative composites for EVA, vehicles and habitats	TDE	T304-020EE	Habitation systems	1	3	Completed	THALES ALENIA SPACE ITALIA SPA	IT
Design of a Scalable Framework of Lunar Habitats	Discovery	20-D-S-TEC-03-e	Habitation systems			Running	Hassel Ltd	UK
Innovative structural material research and manufacturing study for passive radiationprotection for future space missions.	ExPeRT	E2CX-022	Habitation systems	1-2	3-4	Running	Genevation Aircraft Ltd,	HU
Low Cost Hybrid Material Solutions for Radiation and Impact Protection Systems for Human Spaceflight	TDE	T424-418QT	Habitation systems	2	4	Completed	MAGNA PARVA LTD	UK
Rhizome: Development of an Autarkic Design-to-Robotic-Production and -Operation System for Building Off-Earth Habitats	Discovery	20-D-S-TEC-03-b	Habitation Systems			Completed	TU Delft	NL
Small, Inflatable, High Pressure Composite Tanks for Human Spaceflight	TDE	T324-502QT	Habitation Systems	2	3	Completed	THALES ALENIA SPACE ITALIA SPA	IT
Testing of innovative materials for passive radiation shielding for Human spaceflight	TDE	T304-402EE	Habitation Systems	3	5	Completed	THALES ALENIA SPACE ITALIA SPA	IT
Water Storage System for Lunar Life Support and Exploration	Discovery	EISI_11_2021	Habitation Systems	2	3	Running	Sirin Orbital Systems AG	CH

Figure A.6: European ISRU "Habitation systems" activities

Title	Program	Reference	Application	Start TRL	Target TRL	Status	Contractor/Academic	Country
Recovery disassembling and reuse								
Recycling module for waste management in microgravity	TDE	T324-701QE	R&D	2	4	Running	THALES ALENIA SPACE ITALIA SPA	IT
Recycling of Hardware for Moon and Martian Settlement	TDE	T324-602MS	R&D	1	3	Running	OHB	DE
Biodegradable packaging material, waste inhibition and compaction technology for Life Support Systems	TDE	T322-503MM	R&D	1	2	Running	Ghent University	BE
Sustainable materials concepts	TDE	T324-001QT	R&D	1	3	Completed	Astrium Bremen	DE
Towards net zero pollution on the Moon Waste Recycling	ExPeRT	E2CX-045	R&D	2	3	Under Procurement	Orbit Recycling	DE

Figure A.7: European ISRU "Recovery disassembling and reuse" activities

A.1. European ISRU "Cross-cutting" Roadmaps

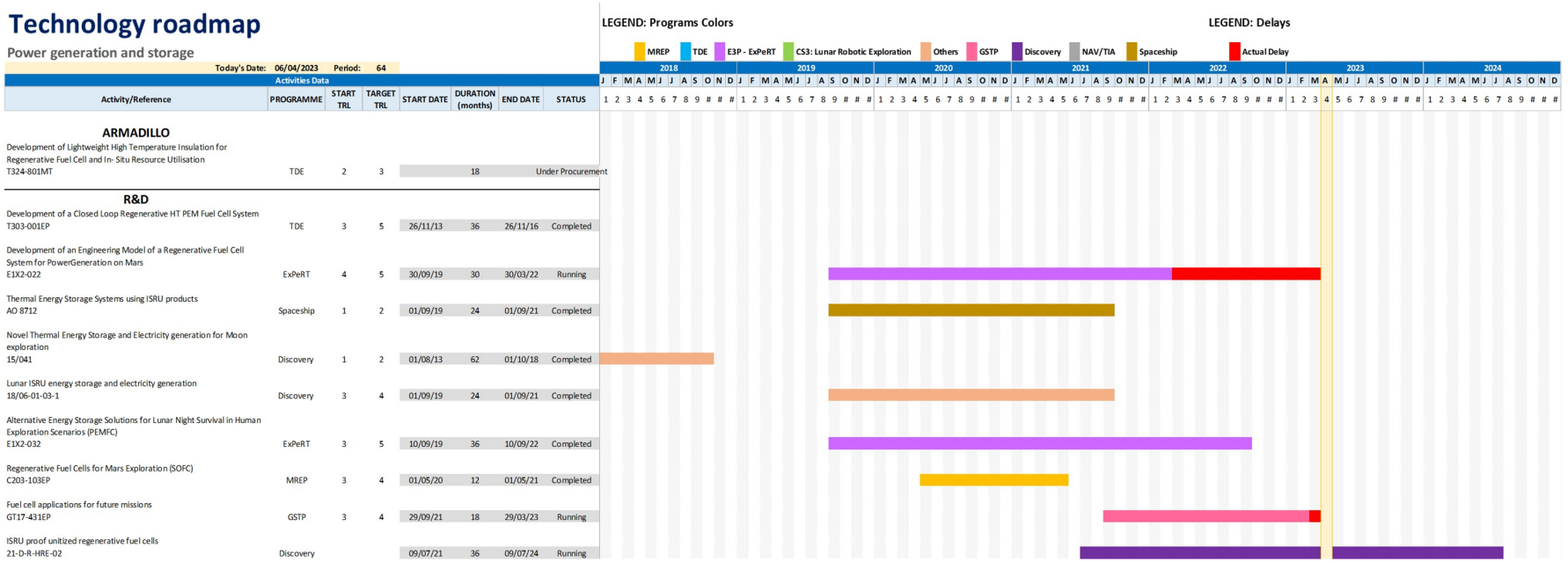


Figure A.8: European ISRU "Power Generation and Storage" Roadmap

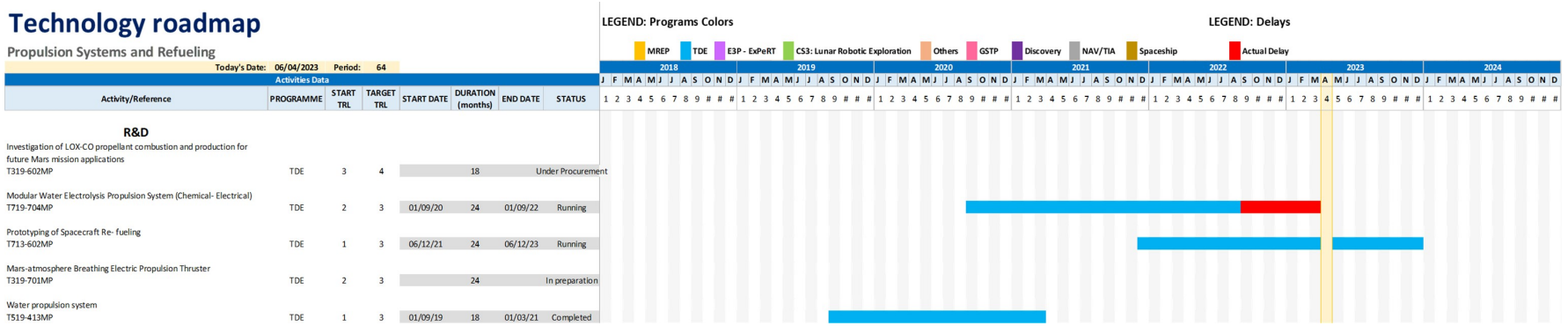


Figure A.9: European ISRU "Propulsion Systems and Refueling" Roadmaps

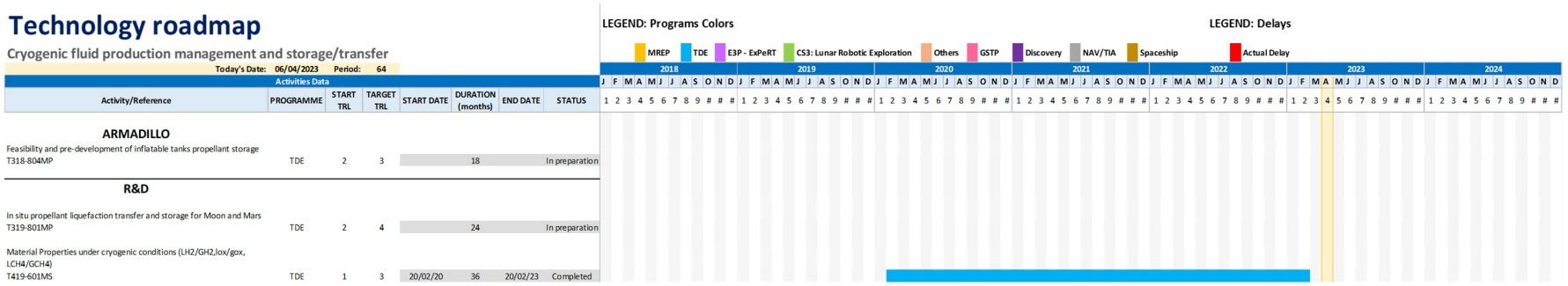


Figure A.10: European ISRU "Cryogenic fluid production management and storage/transfer" Roadmap

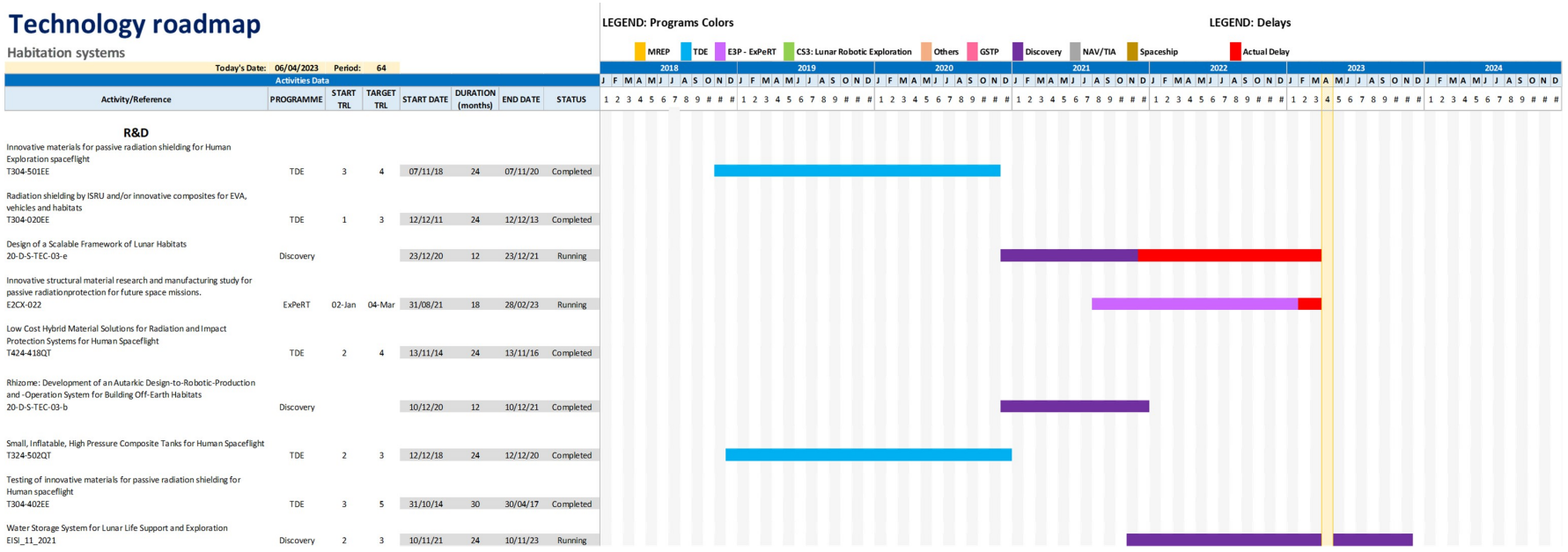


Figure A.11: European ISRU "Habitation systems" Roadmap

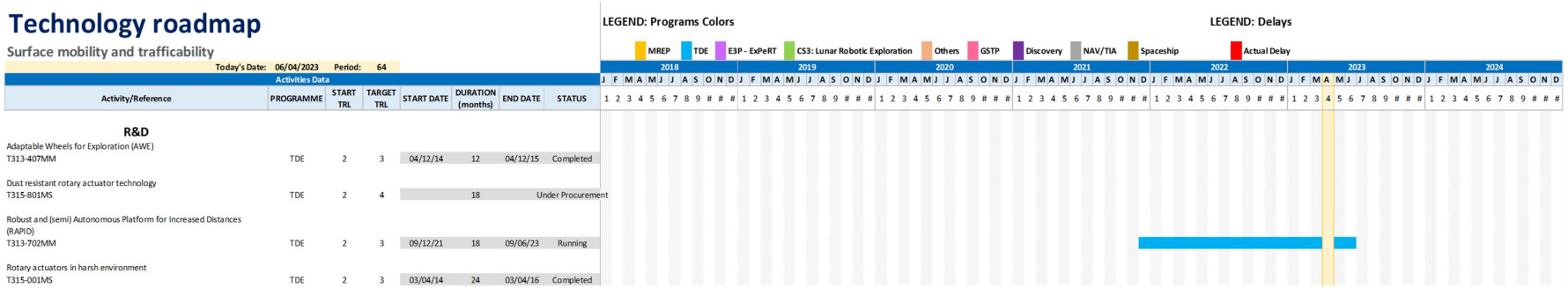


Figure A.12: European ISRU "Surface mobility and Trafficability" Roadmap

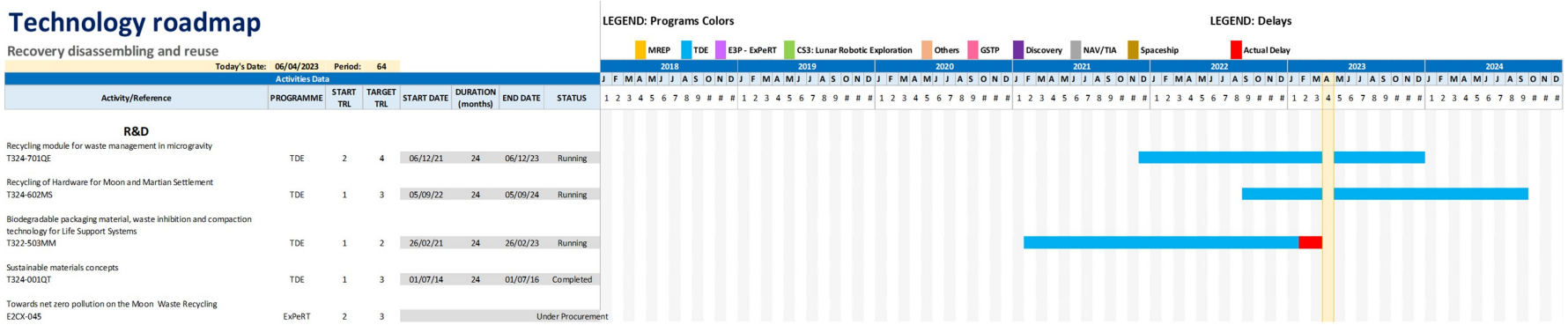


Figure A.13: European ISRU "Recovery disassembling and reuse" activities

Technology roadmap

Dust mitigation

Today's Date: 06/04/2023 Period: 64

Activities Data

Activity/Reference	PROGRAMME	START TRL	TARGET TRL	START DATE	DURATION (months)	END DATE	STATUS
ISRU-DM							
High temperature and dust resistant vacuum seal mechanisms T314-609MSa	TDE	2	4	03/06/20	12	03/06/21	Running
High temperature and dust resistant vacuum sealmechanisms T314-609MSb	TDE	2	4	10/08/20	12	10/08/21	Running
R&D							
Dust removal and cleaning of optical surfaces and seals in lunar environments T314-602MM	TDE	1	3	21/10/20	24	21/10/22	Running
Dust repellant coating technology for future exploration missions T324-601QE	TDE	1	3	09/12/21	24	09/12/23	Running
Effect of a regolith liberated by a rocket plume impingement G619-011MP	GSTP	2	6	18/11/15	24	18/11/17	Running
High Performance SPIS Code for charging effects simulations T304-701EP	TDE	2	4		24		In Preparation
Lunar dust resilient louvered radiators T321-701MT	TDE	1	3	06/09/21	24	06/09/23	Running
Lunar Regolith Interactions with Environments and Robotics Systems 20-D-R-TEC-05	Discovery			22/07/20	36	22/07/23	Running
Electrostatic Charging of Lunar Regolith for In-Situ Resource Utilisation 19-D-R-HRE-01	Discovery	1	3	01/01/20	36	01/01/23	Running
Design and manufacturing of lunar dust simulant for hardware testing N/A	Others	2	5	01/03/20	12	01/03/21	Completed
Characterisation of dust and sample properties in lunar environment T314-007MM	TDE	1	3	08/05/13	12	08/05/14	Completed
Dust electrostatic charging, transport and contamination model for Lunar Lander and human exploration missions T304-002EE	TDE	Algor ithm	Prototy pe	17/11/15	18	17/05/17	Completed
Experimental Validation of regolith/surface probes interactions predictive tools for Exploration T304-702EP	TDE	2	4		18		Under Procurement
Innovative Material for Lunar Passive Dust Mitigation ETD 2021-07	Discovery			21/12/21	18	21/06/23	Running
Lunar Environment Surface Package T304-802EP	TDE	2	3		24		Under Procurement
Modelling and Testing of Plume/Regolith Interaction on Lunar Landing Pads and Berms T318-702MP	TDE	2	4	02/11/22	24	02/11/24	Running

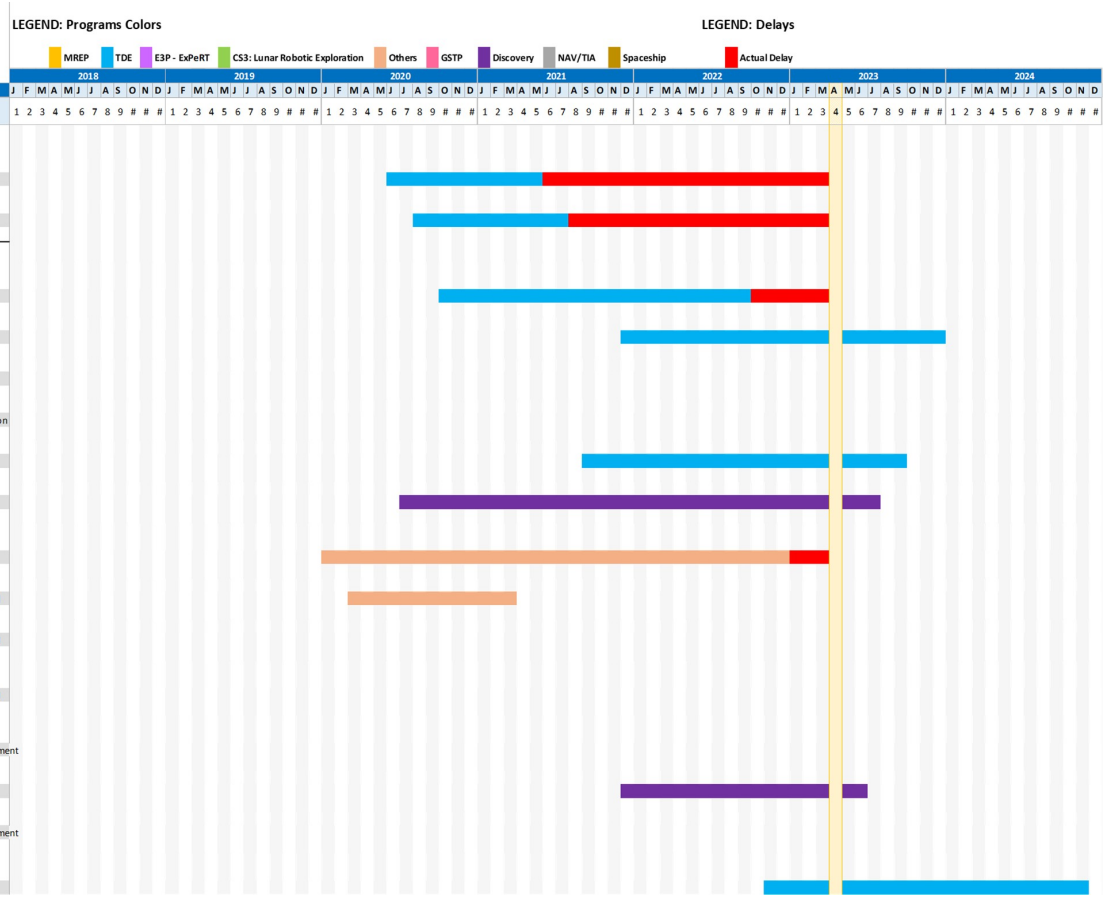


Figure A.14: European ISRU "Dust Mitigation" Roadmap

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