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SMART RESOURCE MANAGEMENT BASED ON INTERNET OF THINGS TO SUPPORT OFF-EARTH MANUFACTURING OF LUNAR INFRASTRUCTURES (SMARTIE)

Barbara Imhof[a*], Robert Davenport[a], Chris Gilbert[a], René Waclavicek[a], Antonella Sgambati[b], Marco Berg[b], Anna Daurskikh[c], Sara Santos[c], Peter Weiss[d], Nisheet Sing[d], Thomas Kaufmann[e], Robert Sorschag[e], Berhard Zimmermann[e], David Binns[f], Advenit Makaya[f]

[a] *LIQUIFER Systems Group GmbH Obere Donaustraße 97/1/62, 1020 Vienna, Austria, barbara.imhof@liquifer.com*
[b] *OHB System AG, Universitätsallee 27, 28359 Bremen, Germany, antonella.sgambati@ohb.de*
[c] *Azimut Space GmbH, Carl-Scheele Straße 14, 12489 Berlin, Germany, anna.daurskikh@azimutspace.com*
[d] *Spartan Space, Rue Lice de Signon, 83170 Brignoles, France, p.weiss@spartan-space.com*
[e] *Zühlke Engineering (Austria) GmbH, Rivergate, 7. Stock, Handelskai 92, 1200 Vienna, Austria, robert.sorschag@zuehlke.com*
[f] *European Space Agency (ESA), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands, advenit.makaya@esa.int*
* Corresponding Author

Abstract

An Off-Earth manufacturing architecture based on a combination of 3D printing and the Internet of Manufacturing Things (IoMT) could provide the smart and efficient management of available resources for long-term survival of both crew and technological assets in harsh space environments. The SMARTIE concept connects the following critical technologies and processes to advance a sustainable exploration scenario:

- Off-Earth Additive Manufacturing machineries
- Off-Earth recycling processes storage systems for end-of-life products and in-situ materials
- Qualitative and quantitative assessment of off-Earth resources
- Off-Earth logistics and navigation systems

Included in this architecture is a communication relay to Earth, and utilization of IoMT networks for the optimization (and control) of printing objects off-Earth, including best choice of printing technology and available material resources. A tracking system for each off-Earth printed item is also envisioned for future recycling at the end of the item's life-cycle; thus, enhancing the self–sustainability of the entire off-Earth manufacturing process. Current industrial developments in intelligence and data processing can be applicable to off-Earth construction, with the potential to streamline manufacturing processes, and devise novel material solutions for printing off-Earth items, valuable to both autonomous building operations and mission crewmembers.

Projects currently underway that support the SMARTIE vision, are the 4G network planned for the Moon, a collaboration between SpaceX, Vodafone, Nokia, and Audi, and the 3D printing technology developed by Israeli company Nano Dimension, capable of printing PCB in layers, especially for IoT needs.

SMARTIE provides an operational system for future network infrastructures considering items such as data management and budget to exploit and optimize Moon Factories Management and available resources to assure high-grade self-sustainability.

Keywords: IoMT, AM technology, Human Lunar Base, Maintenance, Waste Recycling, ISRU

1. Introduction

The Industrial Revolution 4.0 is now underway in Earth-based manufacturing [1]. The application of a smart cloud-based system using the Internet of Manufacturing Things (IoMT) that automatically collects and analyses data from sensors embedded in manufacturing machines allows for improved efficiency of the manufacturing process by controlling raw material utilization, timely response to customer needs, and significantly reducing or even eliminating the need for human intervention [2].

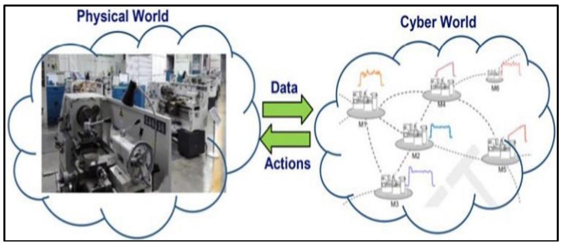

Fig. 1. Industrial manufacturing physical world and representation as a digital twin

IoMT integrates sensors, computing units, physical objects (e.g., machines and tools), and services into a network, thereby forming the backbone of a smart manufacturing system. The IoMT network helps a large number of manufacturing "things" to communicate and exchange data (see Fig.1). With massive data readily available, IoMT presents an unprecedented opportunity to improve the "smartness" of a manufacturing enterprise.

The application of such smart factory technology to human planetary exploration will be a logical extension of such Earth-based systems. The drive to establish human bases for exploration of the Moon initially depends on all resources being transported from Earth which is both costly and time consuming. As such bases evolve it is highly desirable that increasing use is made of both in-situ resources (ISRU–In-Situ Resources Utilization) and re-cycling of waste materials to manufacture products needed for development, maintenance and operation of the base. An IoMT smart factory technology will allow the base to be increasingly independent of transport of resources from Earth with the eventual aim of a fully autonomous operating lunar base (see Fig. 2).

The SMARTIE (Smart resource Management based on Internet of Things to support Off-Earth Manufacturing of Lunar Infrastructures) study reported in this paper aims to describe a concept for a lunar-based smart factory application to forecast and plan maintenance.

SMARTIE is a follow-up to a previous ESA study URBAN [3]. that investigated a concept for a lunar base using 3D printing technologies.

The SMARTIE study is funded by the European Space Agency (ESA) and contracted to a consortium comprising LIQUIFER (Austria) as lead, AZIMUT (Germany), OHB (Germany), SPARTAN (France) and ZÜHLKE (Austria).

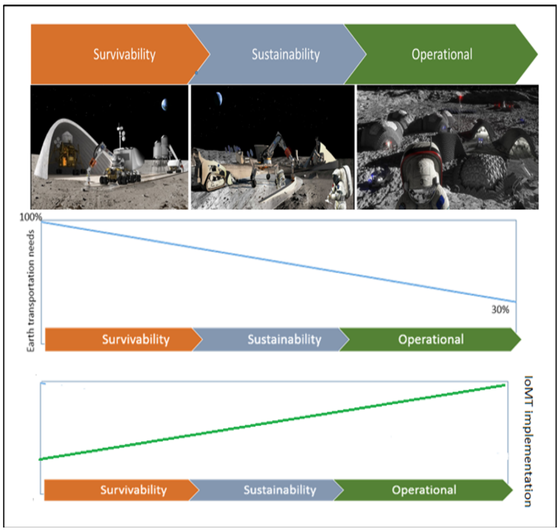

Fig. 2. Evolution of a lunar base and increasing independence from Earth-based support for maintenance

2. IoMT Evolution

Industrial companies are currently facing extensive change. Series production needs to become more customized and single-item production more efficient in terms of resources usage and reuse. Companies need to transform their static processes into flexible added-value networks; implementing a digitization not only in their accounting, customer service and sales departments but also in the factory and warehouse. The goal is clear: production processes that organize and optimize themselves.
This revolution, namely Industry 4.0, is enabled by the recent advances on intelligent automation technology to manage, optimize and automate the manufacturing process.

This concept of Industry 4.0 is synonymous for the transformation of today's factories into intelligent factories, which are designed to meet and exceed the current challenges of shorter product life cycles, highly customized products. High product variability and the reduction of product life cycles require a flexible and agile production structure that can be quickly reconfigured to meet the new product demands. This degree of flexibility cannot be achieved by traditional automation. Instead, modular plant structures composed by intelligent devices, the so-called Cyber-Physical Systems (CPS), which are networked via the Internet of Things (IoT), are key elements to overcome the currently rigid planning and production processes.

Internet of Things (IoT) is a crucial element used to gather information from physical objects using computer networks. The extracted information from embedded sensors placed in products, machines, or production lines constitutes substantial amount of statistical data to be exchanged and analysed and computed to ensure the effective utilization of existing information for smart manufacturing of future. On the other hand, the physical part of the smart factories is limited by the capability of the traditional manufacturing systems; positioning the Additive Manufacturing (AM) as one of the key elements of this new scenario. The goal of this integration is that the control over different manufacturing processes will reduce while it is possible to make the fabrication in fewer steps with less time and material waste leading to a higher benefit–cost ratio.

In their core, both IoT and digitalization are about connecting persons and things with each other. The connection technologies to achieve this at a large scale are already well established using wired technology standards (e.g. Ethernet, RS-232, RS-485, UART, USART, USB) and radio transmission standards (e.g. NFC, Bluetooth, Z-Wave, WiFi, LTE, GSM, LoRA, SigFix).

Another future application of AM is the sustainability issue, in which AM may play a significant role in diminishing waste resources and reducing energy consumption by employing just-in-time production. As a future expectation, decentralization may become possible by distributing the workload over the factories/machines via the effective utilization of cloud services: an outcome of this combination is that a user-specific product can be produced within each machine. This concept is defined as Internet of Manufacturing Things (IoMT) [2].

IoMT integrates sensors, computing units, physical objects (e.g., machines and tools), and services into a network, thereby forming the backbone of a smart manufacturing system. The IoMT network helps a large number of manufacturing "things" to communicate and exchange data. With massive data readily available, IoMT presents an unprecedented opportunity to improve the "smartness" of a manufacturing enterprise.

An IoMT smart factory concept provides an excellent basis for supporting the long-term development and maintenance of a lunar base and its associated elements. An infrastructure with each element having embedded sensors providing status data to a central cloud digital representation of the physical systems will allow for timely manufacture of replacement parts by AM for life-limited or failed items. An IoMT smart factory will reduce significantly the cost and time of bringing parts from Earth. Crew time in space is a precious commodity and maintenance tasks for the crew need to be reduced as far as possible to allow more time for their main task e.g., research, exploration. The enormous quantities of waste that will be produced by an operational lunar base need to be treated as a rich resource that has the potential to be re-cycled into both primary and replacement components.

3. SMARTIE Objectives

The SMARTIE objectives are to define and provide for the needs for a space-based smart manufacturing process to support implementation and operation of a permanent human lunar base, including:

- Assessment of smart management architecture, based on IoMT synergies, for remote operation and monitoring of infrastructures, technologies and material resources in lunar environment.

- Feasibility of implementation of a digitalization of the end-to-end product chain on the Moon, using AM technologies as manufacturing process

- IoMT implementation approach to follow the different stages of the settlement of the Moon base manufacturing infrastructures increasing its sustainability and maintainability.

4. Use cases and benefits implementing IoMT at a lunar base

Factories generate huge amounts of data during production. Equipment in factories is highly interconnected from a physical perspective, but not from an information perspective. With embedded IoT sensor networks and control systems, equipment can be interconnected throughout the factory floor. Manufacturing data, if captured and analysed for insights, can help astronauts identify operational bottlenecks, assure longer uptime, and improve productivity, optimizing the availability of *in-situ* resources and reducing/recycling the waste production.

In this context SMARTIE develops and assesses the feasibility and challenges of an IoMT architecture for the following use cases:

- **Enhance product quality of the printed part**. Machines can use IoT sensor networks to pass data to each other as part of a factory-wide industrial control system. The machines will have a database with default printing parameters and strategy according to the material processed and morphology of the part.

  Benefit: This allows production assets to fine-tune important processing parameters to ensure that products come off the line meeting quality standards. Integrated quality control of the printed parts can be introduced increasing the autonomy of the system and reliability of the end item

- **Ability to forecast and plan maintenance**. On the Moon, the astronauts will be involved in multiple activities and will have only limited time for checking each equipment; IoMT can support the identification of preventative maintenance. In terrestrial applications the IoMT reduces breakdowns by up to 70%.

Benefit: Data gathered from equipment with sensor networks can help both in the manufacturing process and in logistics forecast. This set of information will support the plan for future maintenances and needed resupply from Earth on time. It will reduce the risk to have machines not able to work due to missing parts or replacement of malfunctioned or end of life component.

- **Improve health and safety**. Manufacturers can rest assured that their operations are efficient, as well as compliant with health and safety regulations when they leverage networks of environmental sensors. Temperature, humidity, and other environmental parameters in the factory can affect the quality of the final products. Astronauts can be kept safe and immediately notified of health hazards with IoT sensor-enabled personal protective equipment that monitors environmental conditions in a factory. This is possible with wearable wireless sensors that monitor toxic gases, noise levels, pulse rate, and other health data.

  Benefit: Safe and reliable control and then access to the infrastructures, mainly in a condition of non-permanent crewmembers on the site. Caution & Warning notifications to the crew, as well as evaluation of potential sources of failure to plan maintenance and repair.

- **Maximize the use of available resources** properly and efficiently. Through recycling of items and other resources it is expected that a lot of material is available. The tracking of this material and the recycling processes will be important to trace and control to be able to predict the quality of the product and know how often an item has been recycled.

  Benefit: All the items, infrastructures and components present on the Moon represent a source of raw material for the AM process. The possibility to recycle them in different form and quality reduces the Earth's dependency. Further, the screening of these resources allows us to evaluate the usage and application options and, in this way, to improve the efficiency of their utilization to the final intended use.

The use cases and benefits will be strongly linked to the lunar base evolution, described in the section 6, and available resources and infrastructure.

5. SMARTIE architecture and requirements

To define the SMARTIE requirements, it is first necessary to define the overall architectural concept for a lunar base smart factory application. Fig. 3 shows the roadmap used in this study to achieve these goals. The work flow starts with SMARTIE objectives as defined previously in section 4. The next step is to identify possible use case scenarios for each of the lunar base development phases i.e., ´survivability´, ´sustainability´ and ´operational´ as defined in the URBAN study [3].

Based on the use case scenarios, potential AM technologies are identified for each phase. For each AM technology the typical data provided by the machine sensors to the lunar smart factory cloud database was defined. Also, for each phase typical items and parts were defined that could be subject to AM manufacturing and maintenance in a smart factory environment.

The next step was to take the use case scenarios and the AM technology and sensor data to develop a smart factory architectural concept for each lunar development phase and 'drive out` the SMARTIE requirements.

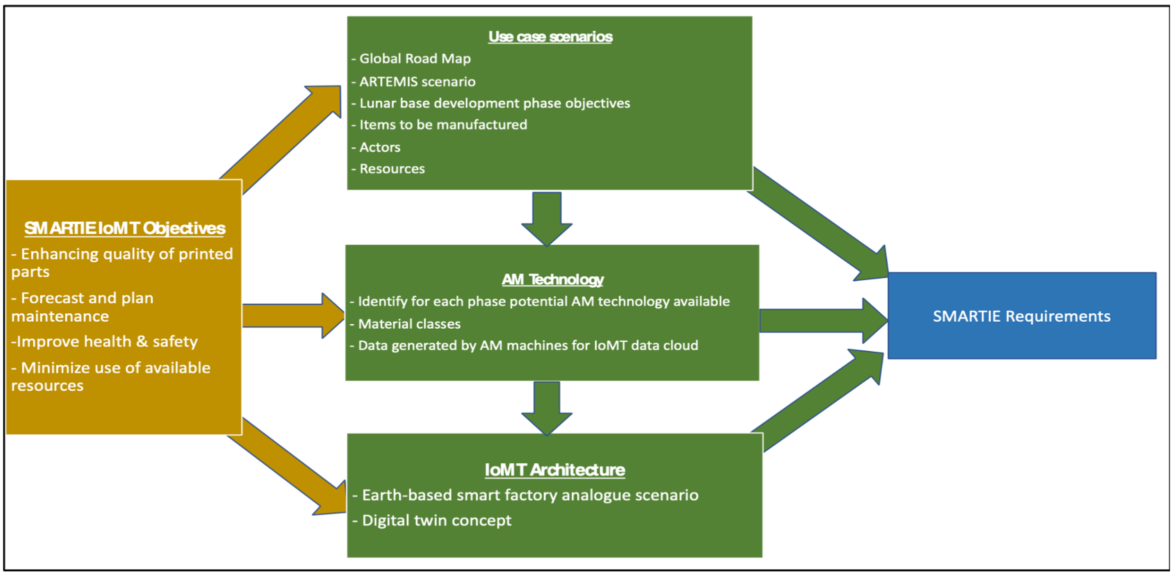

Fig. 3: Roadmap for developing SMARTIE architectural concept and requirements

6. SMARTIE evolution scenarios

The development of a permanent lunar base will be a long-term project lasting many decades. The phased implementation starting with the return to the Moon of humans for short (< 2 weeks) landing site exploration (survivability phase), through longer missions (> 1 month) with initial permanent habitat modules and advanced exploration (sustainability phase) and finally permanent human presence with a fully operational lunar base (operational phase).

During these lunar base development phases, there will be a gradual build-up of permanent infrastructure (see Fig. 4) that will require repair and maintenance. Re-cycling of materials and manufacture of replacement parts will become a necessary feature of an advanced lunar base in order to reduce transport of materials and parts and even large structures from Earth (and hence costs).

Exactly how the lunar base build-up will take place depends on a large number of factors that are difficult to foresee particularly over time scales of decades. Hence for this study the Global Exploration Roadmap [4] has been selected as the scenario most likely to be followed by international partners in the Artemis program (see Fig. 5 in Appendix A). Other proposed lunar base developments by China and Russia are not considered as a baseline scenario here as they are presently not detailed enough. Nevertheless, this may change in the next decade. IoMT-architectures such as SMARTIE would in principle also be applicable to such a China/Russia lunar base.

Fig. 5 (see Appendix A) shows a proposed mapping of the survivability, sustainability and operational phases to the Global Exploration Roadmap. The transition from one phase to the next depends largely on the availability of resources for sustaining human presence for increasing durations of lunar surface exploration campaigns.

In order to differentiate these three phases, the arrival of key elements on the lunar surface is proposed:

The **Survivability** phase of crewed lunar surface activity will start with the arrival of the first human crews on the surface. Very few assets will be available at this stage for manufacturing items. The Global Exploration Roadmap shows rovers and small habitation elements apart from the human landing system. ISRU extraction and in-situ fabrication elements will only be demonstrators at this stage.

The next phase, **Sustainability**, will start when the first in-situ production elements are installed on the surface. At this stage local crews will have the possibility to produce, repair and maintain items on the surface.

The **Operational** phase will start beyond the horizon of what is illustrated in Fig. 5: Crews will be permanently stationed on the lunar surface similar to ISS or terrestrial analogues such as Concordia. At this stage surface equipment should include significant production means to maintain the lunar base operational and to allow crews to live and work there. This will not only include exploration activity but potentially also commercial activity.

Figs. 6-8 are a proposed way of drawing pictures of future surface production scenarios. For each scenario a short resumé is listed with main elements of the respective stage. The objectives of the applicable phases are presented at the left (they do not significantly differ of course from one phase to another).

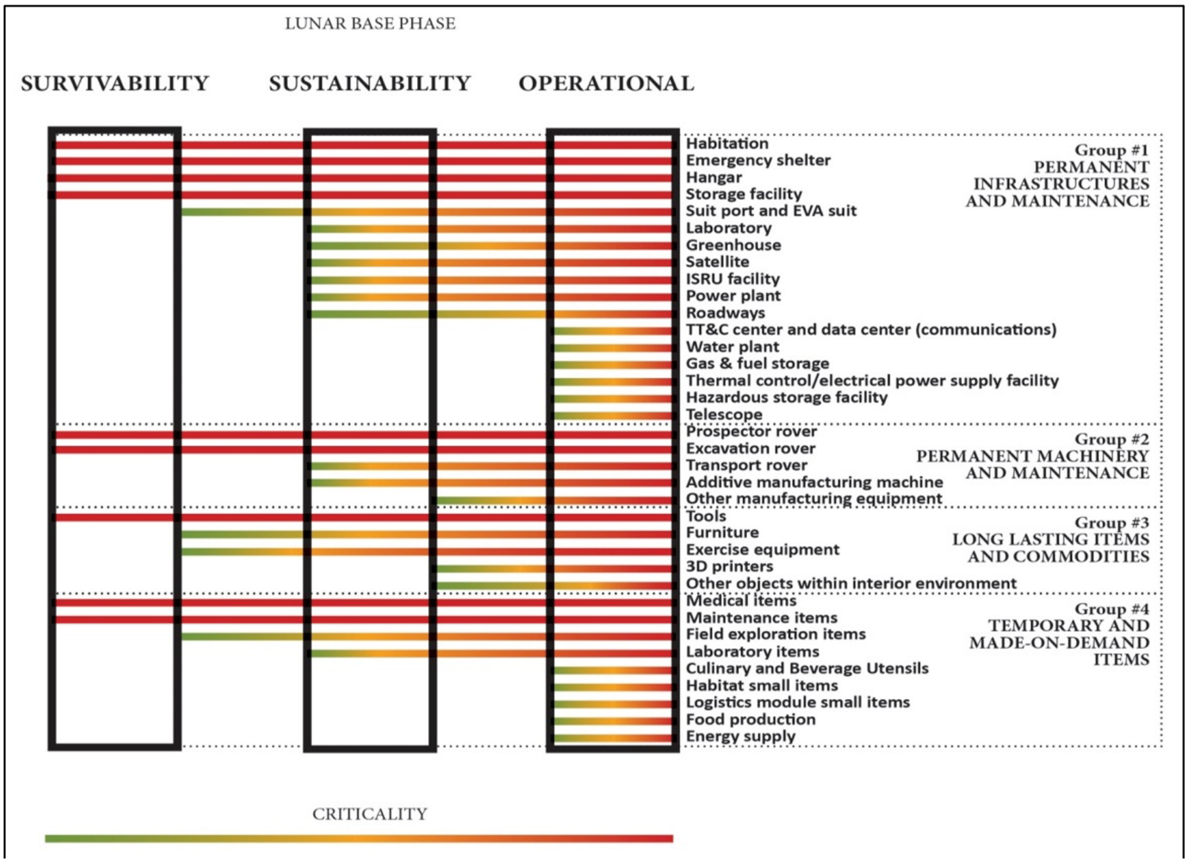

Fig. 4: Phased lunar base growth and infrastructure criticality (Source: ESA URBAN study [3])

The next columns list items to be manufactured at each stage, the actors involved (hardware elements and cloud data) and resources available for an IoMT smart production.

As stated previously the material available to fulfil the SMARTIE objectives will increase through the various phases allowing for ever more complex parts production and in larger quantities if needed.

7. Resources for a lunar base smart factory

A wide range of materials will be available to a lunar base smart manufacturing facility. Such resources range from ISRU (e.g. regolith, water/ice) through recycled elements generated by the lunar base and its various recycled elements generated by the lunar base and its various facilities and associated exploration and scientific equipment.

The required resources for a lunar smart factory are based on two critical parameters, namely, application and material types. Materials on the lunar surface can be made available by in-situ resources like lunar dust, regolith, water and ice, recycling or brought from Earth.

Based on the output of URBAN [3] study the different types of materials in relation to the applications have been categorised in four groups:

Group1 are permanent infrastructures and maintenance of those (e.g., habitats, hangars but also space suits).

Group 2 are permanent machinery and maintenance of such equipment (e.g., robots/rovers, 3D printers).

Group 3 are long-lasting commodities that are mainly found in the interior of a habitat (e.g., furniture, training equipment).

Group 4 are temporary and made-on-demand items such as food, medical devices but also tools.

The materials that can be used on the lunar surface are sparse: some in-situ materials are obviously available such as lunar dust and regolith. Also, water and ice are a resource that needs to be taken into account maybe not only to sustain life and plant growth but potentially as construction element (water is a good radiation shield). Further on there are metals that can be either extracted on the lunar surface in a long-term vision or be recycled on the surface or brought from Earth. Glass products and fibreglass can be an element in more complex material compositions. As a derivation of regolith it might be produced directly in-situ or potentially recycled or be brought from Earth. Plastics and rubber are more complex raw materials that need to be brought from Earth or being recycled on the surface. The list is completed by materials of biological origin (cellulose, wood). It could be imagined that these are grown in-situ on the surface, or they are recycled or brought from Earth.

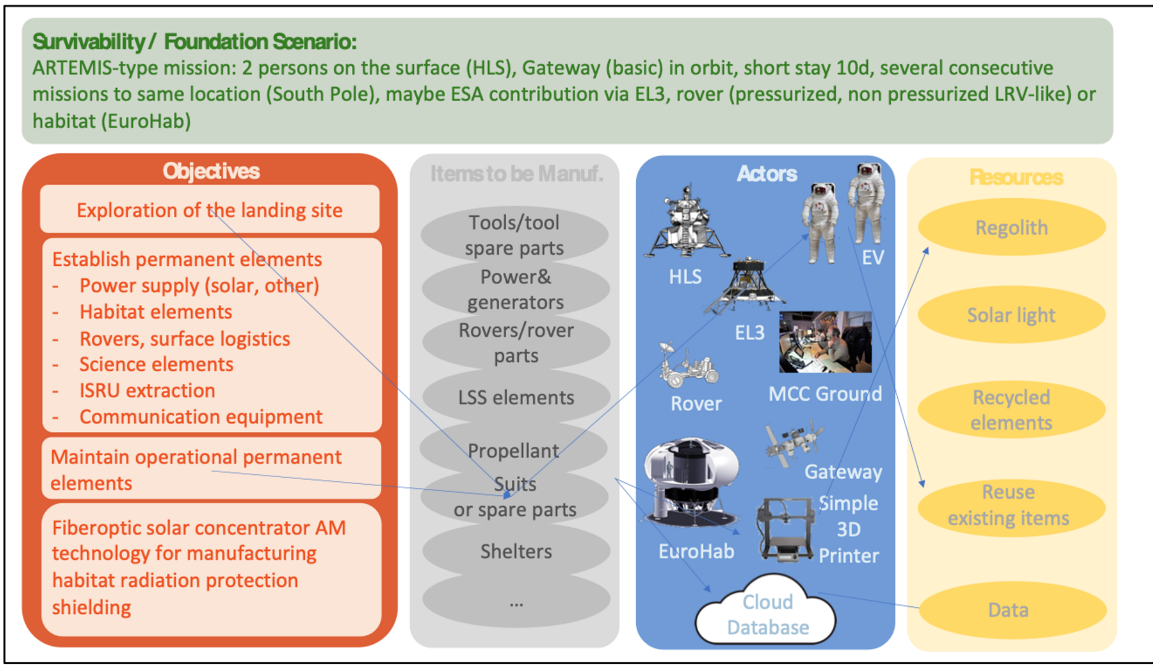

Fig. 6: Survivability scenario depicting objectives, potential items to be manufactured, actors and resources

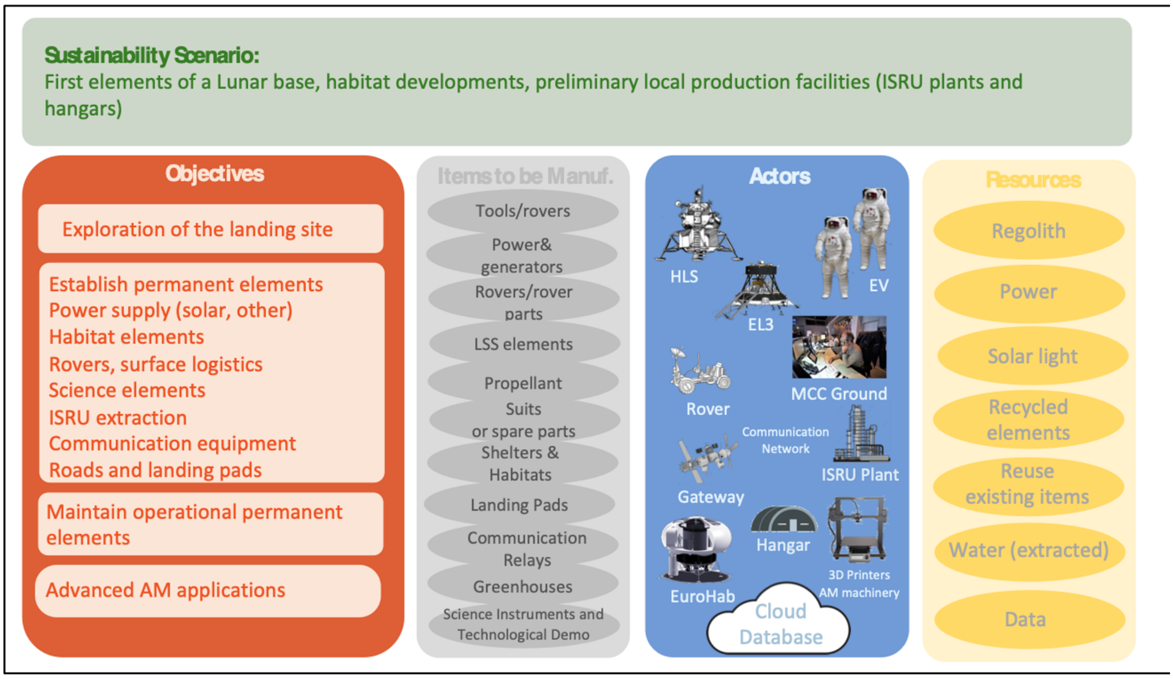

Fig. 7: Sustainability scenario depicting objectives, potential items to be manufactured, actors and resources

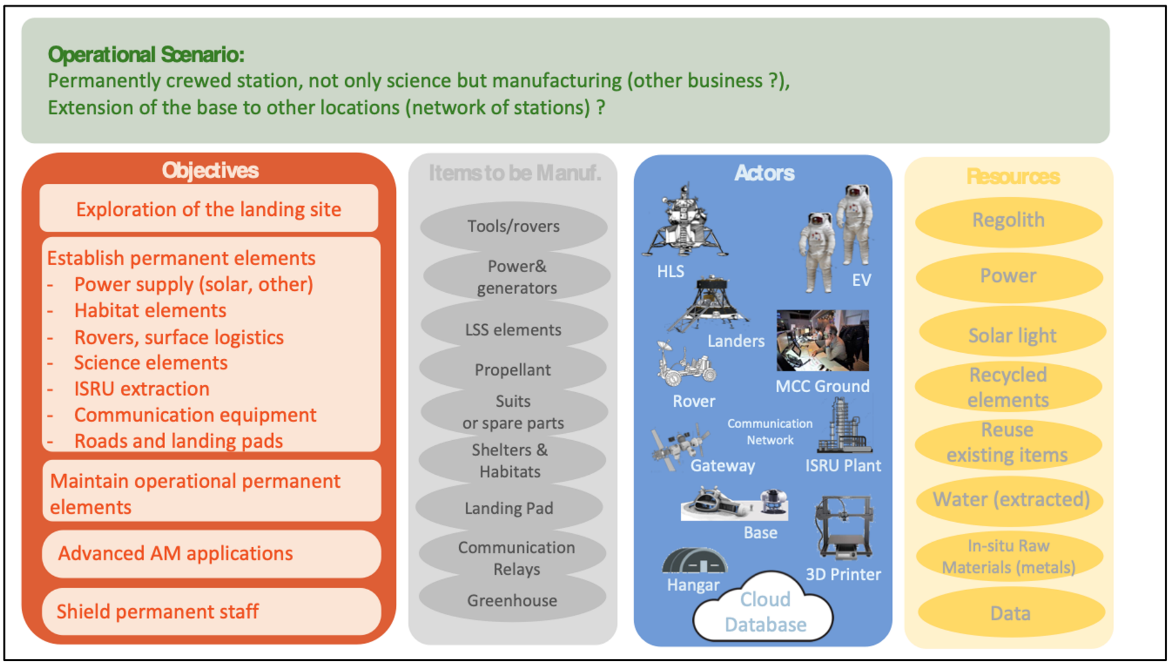

Fig. 8: Operational scenario depicting objectives, potential items to be manufactured, actors and resources

8. AM technologies

The additive manufacturing (AM)[5] technologies that will be available to a lunar smart factory will depend significantly on the development phase of the lunar base. In order to select suitable AM technologies for each of the phases, the results of the URBAN study were used. This study created a database of additive manufacturing technologies, and ranked them in terms of applicability to the Moon base construction using a utility function calculated using key performance indicators, such as: for how many objects can this printer be used, number of different materials that can be processed, influence of low gravity on the process, power requirements, recycling capabilities and feedstock sourcing. Based on the value of the utility function, a shortlist was created, and it was also considered, that even though some technologies can be capable of processing only one material, they should be shortlisted if the material is critical for the infrastructure, such as regolith.

In this study, technologies from the URBAN shortlist were reviewed and their current development assessed, and then technologies for implementation during different stages of Moon base construction were selected.

The AM technologies are implemented in an order based on the elements of the infrastructure that need to be constructed and repaired. The survivability phase marks the start of large infrastructure manufacturing such as roads and shielding for habitats from regolith, relying on **Solar Concentrators (SC) and Contour Crafting (CC)**[6] technologies. Solar Concentrator uses solar energy to sinter regolith, and Contour Crafting is an extrusion-based technology that prints with a mix of regolith and binder. In the pressurized lab environment, use of desktop **Fused Filament Fabrication (FFF) printers** is foreseen for the production of small and medium-sized spare parts and tools. These printers can process a wide range of plastics, including feedstocks with additives, such as a mix of plastic and rubber or plastics with metal or magnetic particles.

In the sustainability phase, more power will become available, and more construction and repair will be performed in-situ. Therefore, AM technologies allowing the manufacturing of large-scale metal and plastic parts, **Electron Beam Additive Manufacturing (EBAM)** and large-scale hybrid FFF with CNC are added. The former uses metal wire and can be used in unpressurized environment to create metal structures. Recycling facility for polymers will become operational to allow sustainable use of resources and increase independence from re-supply missions.

Finally, in the operational phase, the range of available AM technologies is expanded to allow processing other material types. The selected technologies are **Lithography-based Ceramic Manufacturing (LCM)** for production of ceramic parts, and **Direct Ink Writing (DIW)** that is used together with FFF to offer flexibility of multi-material printing.

9. Use Case scenario assessment

The possibility of reducing the Earth dependency by making maximum use of both existing lunar surface materials and re-cycling of lunar base materials to 3D print a host of items such as structural elements, module exterior / interior fittings, solar cells, food, replacement parts, and one-time needs provides the only programmatic solution to assure a sustainable settlement. Therefore, the forecast and maintenance use case, benefitting from IoMT, represents a crucial assessment in supporting the sustainable and feasible implementation of long-term operation of off-Earth human settlements. The main features will be:

- Automatic reports on the inventory list to provide data about available raw materials, consumables and spares
- Statistics on the failure rate of the manufacturing machines, devices and hardware, as input to the logistics plan and manufacturing capability
- Planning of the crew time in replacing and/or repairing parts
- Operational hours of the machine to determine the end of life.

The forecast and maintenance data will evolve and expand according to the lunar base evolution. The main objective will be to assure a reliable manufacturing capability to support on demand the user needs. Therefore the first step will be to predict the failure rate of the AM machines and recycling system to assure a continuous running manufacturing plant (**Forecast and Maintenance of the IoMT**) The AM devices will expand according to the lunar base development stage (survivability, sustainability or operational), then the identification of the critical parts subjected to high probability of failure will be the initial items to be printed in–situ or brought from Earth (**Forecast and Maintenance of the Moon infrastructure)** This decision process is strongly conditioned by the material available and possibility to process it with the available AM.

In fact, during the survivability phase the AM machines are focused on the construction of large infrastructures made of lunar regolith. It is expected that at the beginning of the base settlement, the spare parts for critical subsystems will be launched from Earth instead of being printed in-situ. This trend will change along with the lunar base evolution, evolving to more AM capability in processing a broad range of materials with improving accuracy.

9.1 USE CASE for forecast and Maintenance of the IoMT

Objective: Achieve a self-sustained manufacturing plant able to support the on-demand or planned H/W production in-situ.

At the survivability stage the AM machines available will be mainly the FFF, Solar concentrator and Contour Crafting (CC) [7].. Each technology is assessed at subsystem level to identify the critical parts subjected to failure, which will require in-situ maintenance even if at this stage it is expected that spare parts and consumables will be largely uploaded from Earth together with each device.

For the CC the nozzle, hopper, and material delivery system are the main components. The hopper is made of metal (e.g., Stainless Steel) and can be considered as use case to be printed by FFF.

9.2 USE CASE for forecast and Maintenance of the infrastructure

Objective: Assure support in-situ to repair and maintain actual infrastructures.

At the survivability stage the H/W present on the lunar surface is limited (see Fig. 6). SMARTIE will analyse a subset of the individual components of major items such as the habitat (e.g., structural elements, solar panels), rovers (e.g., wheels, thermal protection) and space suits (e.g., visors, suit joint bearings, suit material layers) to identify a subset of items that could be printed with the 3 AMs machines available in this phase.

SMARTIE uses a similar approach for use cases in the sustainability and operational lunar base scenarios thus providing a basis for the architectural concept of the required IoMT infrastructure.

10. SMARTIE Architecture Design Concept

The following section commences with an overview of the study objectives, followed by an elaboration of use case scenarios, actors, and resources. It then concludes by bringing these concepts together in a high-level contextual view of the SMARTIE IoMT manufacturing system and outlines core system components.

Based on the identified scenarios in section 6, Fig. 9 (see Appendix B) illustrates the spatial distribution of SMARTIE's primary actors and system components throughout the evolutionary phases.

The survivability phase is envisioned to establish core infrastructure components comprising communication networks, computational resources and further system components required by a fundamental IoMT system for first human surface activities and future missions. This infrastructure is expected to be established incrementally, requiring systems to properly scale horizontally, with energy availability and transportation capacities being the major limiting factors. As mentioned before, initially, this phase will also not be rich in AM technologies and machines but constitutes core system components to orchestrate and monitor manufacturing processes, manage resources and production plans as well as interfaces for user interaction.

As activity in the lunar base increases and more power as well as AM technologies become available, the SMARTIE cloud approaches the sustainability phase, where demands for increased scale as well manufacturing complexity arises. In this phase, the limited set of static AM machinery and technology from the foundation phase increases substantially, supporting a variety of technologies thereby enabling complex manufacturing workflows of items. Even more, this phase is characterized by preparing for long-term habitation. Thus, an infrastructure for precise monitoring of processes, actors and environmental conditions needs to be established, as a foundation for self-optimizing data-driven processes and workflows.

In the sustainability phase where the demands for increased scale as well manufacturing complexity increase substantially, the initial IoMT foundation, previously focusing on simple per-request manufacturing processes, will evolve in different directions. First, as energy limitations decrease, more advanced AM technologies will be established in the lunar base, potentially acting and interacting dynamically in and with the environment; advanced process planning and decision support engines are required, in order to autonomously devise appropriate manufacturing workflows, while considering resource restrictions.

The operational phase is characterized by preparing for long-term habitation, capabilities for environmental and component status monitoring will be established. This information can enhance fine-grained information on material compositions to optimize future manufacturing processes.

Finally, as the scale and the capabilities of the lunar-based IoMT to produce complex parts increases, artifact life-cycle management shall be established, providing capabilities to track locations and maintenance periods, and eventually manage end-of-life events and recycling procedures.

11. Outlook & Recommendations

The next steps in the study will display how the AM technologies tie into the availability of resources and how they can help to forecast material wear to assure timely availability of needed parts for the successful completion of long-term missions, and to establish a lunar factory with a smart management on the Moon. A first Use Case for Forecasting and Maintenance will be described indicting the key technology developments for an IoMT Architecture.

The SMARTIE study directly connects to ESA's Moonlight initiative [8]. Moonlight shall provide telecommunications and navigation services for missions to and on the Moon. This infrastructure would enable missions to land at any point on the lunar surface and be connected to all infrastructure on the lunar surface, and to Earth. For example, a radio telescope on the lunar far side could be part of the network and give easy access to astronomers on Earth to utilize the data and research from the far side; or rovers could be directly teleoperated from Earth; on the moon vehicles could increase their speed through being connected to Moonlight. A SMARTIE IoMT could also connect to NASA's Lunarnet, a similar approach to the ESA Moonlight initiative. In this way a SMARTIE-based IoMT would connect communication systems with lunar infrastructure and thus enhance the ability to forecast resources, and produce and maintain equipment on the lunar surface. Such an IoMT Architecture would allow for a long-term presence on the moon and support the creation of an autonomous lunar eco-system of infrastructures, production facilities. This would contribute to the enhancement of mission sustainability. SMARTIE is conceived as a study for an IoMT Architecture that ties all kind of actors together with a great potential for international cooperation. It is staged in its development phases so it can grow over time with a relatively small up-front investment. This is also due to the light-weight of the actual hardware which considerably reduces launch costs, presenting a valuable infrastructure of great use to all at a moderate price. Such development could also be beneficial to IoMT developments for autonomous infrastructures on earth.

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Appendix A: Global Exploration Roadmap and SMARTIE lunar base development phases

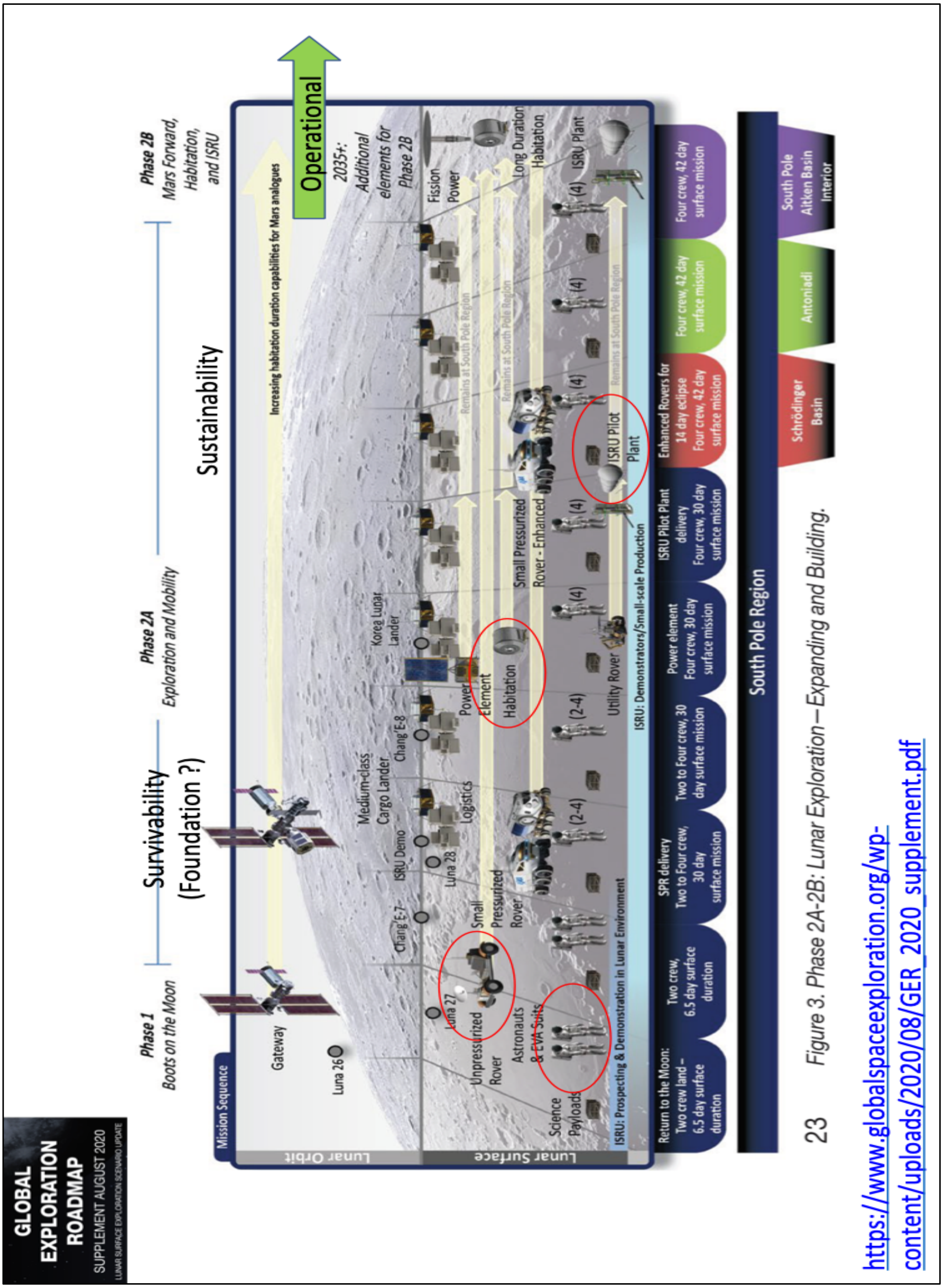

Fig. 5: Global Exploration Roadmap and proposed mapping of lunar base development phases

Appendix B: Initial Architectural Concept for SMARTIE

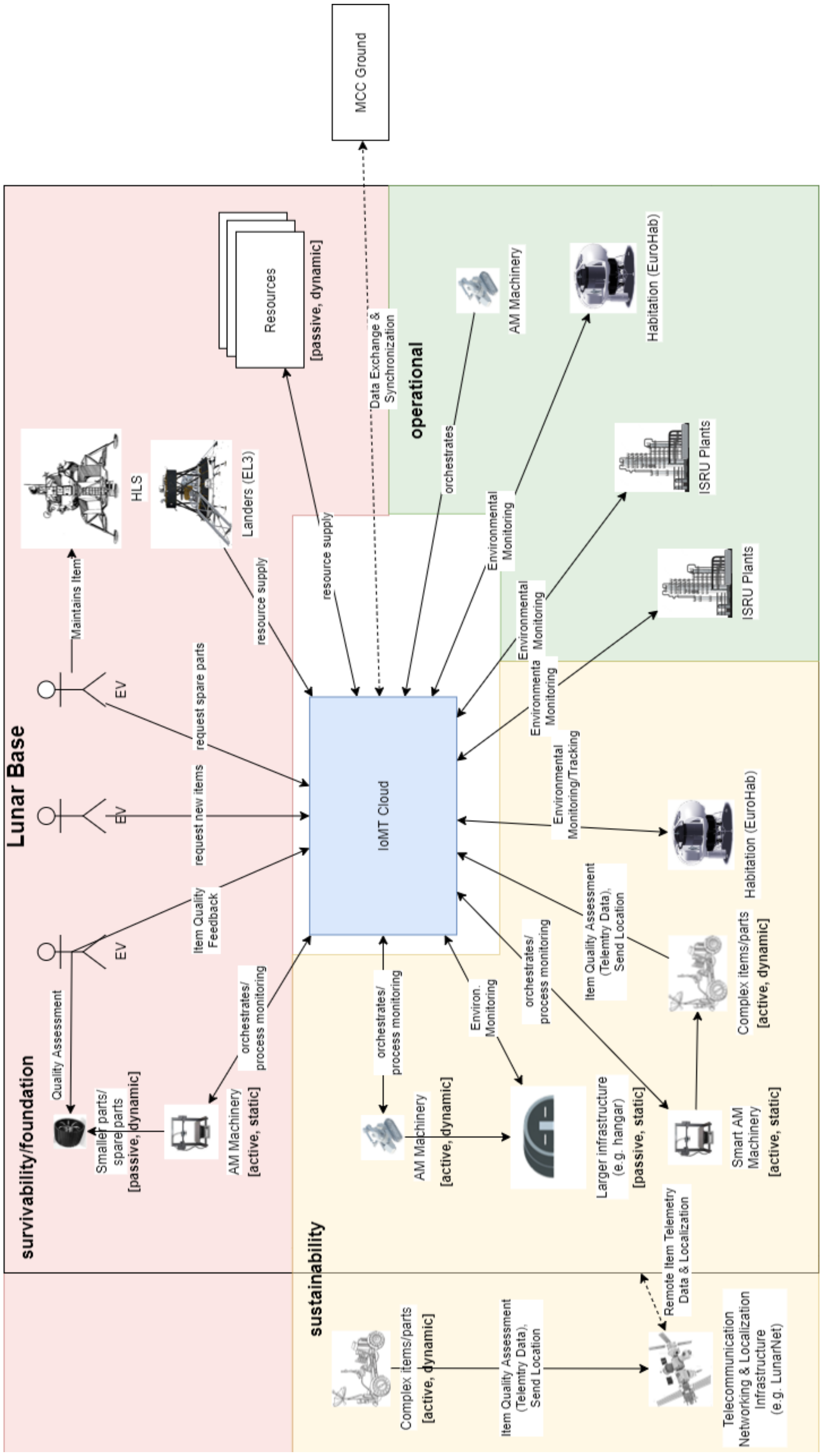

Fig. 9: Overview of an initial architecture for a lunar-based smart factory in each of the lunar base development phases