Augmented Reality in a Planetary Greenhouse for Crew Time Optimization

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The following people served as advisors for this thesis:

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Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university.

Conrad Zeidler

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für Magdalena

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Montreal, April, 2024 Conrad Zeidler

Abstract

The Artemis campaign aims to return humans to the Moon by the late 2020s, nearly 50 years after the last Apollo astronauts walked on the lunar surface. As a precursor for missions to Mars, long-term and self-sustaining habitats are planned to be deployed on the Moon by the mid-2030s. A vital element of these habitat infrastructures will be planetary surface greenhouses capable of producing fresh food and recycling the habitat's air and water, reducing the need for (re-)supplies from Earth. Furthermore, plant cultivation benefits the crew's psychological well-being during space missions. For these reasons, several space agencies (e.g., ASI, CSA, DLR, and NASA) are investigating planetary surface greenhouses for bioregenerative life support.

Research has shown that crew time is a valuable but limited resource during space travel and that the mission's success depends on the proper allocation of crew time. Therefore, crew time must also be optimized for operations of planetary surface greenhouses, especially to dedicate sufficient time for scientific activities. Furthermore, the perceived workload of planetary surface greenhouse operators (astronauts) must be reduced as much as possible. To accurately estimate the crew time and workload required for greenhouse operations, engineers and mission planners rely on the data gathered from space analog facilities and space station plant experiments. However, past research has shown a paucity of comparative crew time and workload data. Furthermore, existing crew time datasets are difficult to compare as no standardized measurement approaches exist.

In this thesis, investigations were conducted to determine how workload and crew time could be optimized for the operations of planetary surface greenhouses. The first part of the thesis investigated two space research-related questions: (**RQ1**) How can crew time measurements be standardized for better comparability? and (**RQ2**) How much crew time and workload are required in a space greenhouse?

In response to these research questions, the investigations in the first part of this thesis resulted in four key contributions: (**C1**) Databases of crew time and workload values for space greenhouse operations have been created, (**C2**) Conclusions were drawn about what factors affect crew time and how their characteristics differ for greenhouses used in various space mission scenarios, (**C3**) Recommendations were made on which of the tasks/procedures studied should be simplified, automated, or remotely supported to reduce the workload of space greenhouse operators, and (**C4**) Methodologies were developed to standardize the crew time measurements for on-site operator activities in space greenhouses and associated remote support activities.

Two new research questions emerged from these results: (**RQ3**) What features should be integrated into an augmented reality interface used in a space greenhouse to facilitate workflows for on-site operators and remote support teams on Earth? and (**RQ4**) How should immersive technologies such as augmented reality interfaces be designed and developed to reduce the crew time and workload of astronauts and remote support teams on Earth when operating a space greenhouse?

An interdisciplinary approach was chosen to address these research questions arising from the challenges of space exploration. The importance of augmented reality for workflow optimization has increased in recent years in various application areas. For this reason, the second part of this thesis focused on computer science-related investigations for implementing augmented reality in planetary surface greenhouses to optimize workload and crew time. Investigations outlined in this part resulted in four key contributions to the research field: (**C5**) A conceptual design of an augmented reality interface for a planetary surface greenhouse was presented, (**C6**) A new tool for real-time plant detection and augmentation running directly on an augmented reality headset was developed, (**C7**) A novel and relatively simple approach was developed for in situ generation and visualization of plant health (plant stress) information on an augmented reality headset for use in space greenhouses, and (**C8**) The benefits and relevance of augmented reality applications for the design, optimization, and operations of greenhouses used during space missions were demonstrated.

Overall, the values and research on crew time, workload, and utilization of augmented reality applications presented in this thesis have significant implications for the design and operations of future planetary surface greenhouses and the planning of related space missions. These results can equally improve the reliability and efficiency of operations in today's terrestrial food production systems, such as greenhouses and vertical farms, making the findings immediately applicable and relevant on Earth. While the findings have expanded the limited research on operations and augmented reality applications for planetary surface greenhouses, additional research is still needed.

Zusammenfassung

Fast 50 Jahre nachdem die letzten Apollo-Astronauten die Mondoberfläche betreten haben, werden im Rahmen der Artemis-Kampagne Ende der 2020er Jahre wieder Menschen auf dem Mond landen. Als Vorbereitung für Marsmissionen sollen dort bis Mitte der 2030er Jahre langfristige und autarke Habitate errichtet werden. Ein wesentliches Element dieser Habitate werden Gewächshäuser zur Produktion von frischen Lebensmitteln und zum Recyclen von Luft und Wasser sein. Die Gewächshäuser auf der Mondoberfläche werden den Bedarf an Versorgungsflügen von der Erde verringern. Darüber hinaus trägt der Pflanzenanbau auch zum psychischen Wohlbefinden der Astronauten während der Weltraummissionen bei. Daher planen mehrere Raumfahrtagenturen (z.B. ASI, CSA, DLR und NASA) Gewächshäuser auf Planetenoberflächen zur bioregenerativen Lebenserhaltung.

Die Forschung hat gezeigt, dass Crew-Zeit eine wertvolle, aber begrenzte Ressource in der Raumfahrt ist und der Missionserfolg von der richtigen Crew-Zeitverteilung abhängt. Daher muss die Crew-Zeit auch für den Gewächshausbetrieb auf Planetenoberflächen optimiert werden. Außerdem muss die empfundene Arbeitsbelastung für den Gewächshausbetrieb reduziert werden. Um die Crew-Zeit und Arbeitsbelastung für den Gewächshausbetrieb genau abschätzen zu können, stützen sich Ingenieure und Missionsplaner auf Daten von Forschungsanlagen unter weltraumanalogen Bedingungen und Pflanzenexperimenten auf Raumstationen. Die bisherige Forschung hat jedoch gezeigt, dass nur wenige vergleichende Daten zu Crew-Zeit und Arbeitsbelastung zur Verfügung stehen. Darüber hinaus sind die vorhandenen Crew-Zeit Datensätze schwer zu vergleichen, da es keine standardisierten Messverfahren gibt.

In dieser Arbeit wurde untersucht, wie der Gewächshausbetrieb auf Planetenoberflächen in Bezug auf Crew-Zeit und Arbeitsbelastung optimiert werden kann. Im ersten Teil der Arbeit wurden zwei Fragen aus der Weltraumforschung untersucht: (**RQ1**) Wie kann die Messung der Crew-Zeit standardisiert werden, um eine bessere Vergleichbarkeit zu erreichen? und (**RQ2**) Wieviel Crew-Zeit und Arbeitsbelastung sind in einem Gewächshaus für den Betrieb im Weltraum erforderlich?

Die Untersuchungen des ersten Teils dieser Arbeit lieferten vier wesentliche Beiträge zur Beantwortung dieser Forschungsfragen: (**C1**) Datenbanken mit Werten zu Crew-Zeit und Arbeitsbelastung für den Gewächshausbetrieb im Weltraum wurden erstellt, (**C2**) Es wurden Schlussfolgerungen gezogen, welche Faktoren sich auf die Crew-Zeit auswirken und wie sich deren Eigenschaften für Gewächshäuser in verschiedenen Weltraummissionsszenarien unterscheiden, (**C3**) Weiterhin wurden Empfehlungen gegeben, welche der untersuchten

Aufgaben/Prozeduren vereinfacht, automatisiert oder ferngesteuert werden sollten, um die Arbeitsbelastung der Astronauten zu reduzieren, und (**C4**) Schließlich wurden Methoden zur Standardisierung der Messung der Crew-Zeit von Astronauten für den Gewächshausbetrieb und der damit verbundenen Fernunterstützung durch Remote Support Teams entwickelt.

Aus diesen Ergebnissen ergaben sich zwei neue Forschungsfragen: (**RQ3**) Welche Funktionalitäten sollten in ein Augmented Reality Interface integriert werden, das in einem Weltraumgewächshaus eingesetzt wird, um Arbeitsabläufe für Astronauten und die Remote Support Teams auf der Erde zu erleichtern? und (**RQ4**) Wie sollten immersive Technologien wie Augmented Reality Interfaces konzipiert und entwickelt werden, um die Crew-Zeit und die Arbeitsbelastung der Astronauten und der Remote Support Teams auf der Erde für den Gewächshausbetrieb auf Planetenoberflächen zu reduzieren?

Zur Beantwortung dieser Forschungsfragen mit Ursprung in der Weltraumforschung, wurde ein interdisziplinärer Ansatz gewählt. Die Bedeutung von Augmented Reality zur Arbeitsablaufoptimierung hat in den letzten Jahren zugenommen. Aus diesem Grund konzentrierte sich der zweite Teil dieser Arbeit auf computerwissenschaftliche Untersuchungen des Einsatzes von Augmented Reality zur Optimierung der Arbeitsbelastung und der Crew-Zeit in Gewächshäusern auf Planetenoberflächen. Die in diesem Teil vorgestellten Untersuchungen führten zu vier wesentlichen Beiträgen zum Forschungsfeld: (**C5**) Ein Konzept für eine Augmented Reality Anwendung für Gewächshäuser auf Planetenoberflächen wurde vorgestellt, (**C6**) Es wurde ein neues Tool für die Echtzeitpflanzenerkennung und -augmentierung entwickelt, das direkt auf einem Augmented Reality Headset läuft, (**C7**) Weiterhin wurde ein neuartiger und relativ einfacher Ansatz für den Einsatz in Weltraumgewächshäusern erarbeitet, um Informationen über die Pflanzengesundheit (Pflanzenstress) vor Ort auf einem Augmented Reality Headset zu generieren und zu visualisieren, und (**C8**) Die Vorteile und Relevanz von Augmented Reality Anwendungen für die Entwicklung, die Optimierung und den Betrieb von Gewächshaussystemen für Weltraummissionen wurde demonstriert.

Die Forschungsergebnisse dieser Arbeit haben bezüglich Crew-Zeit, Arbeitsbelastung und des Einsatzes von Augmented Reality Anwendungen eine große Bedeutung für das Design und den Betrieb zukünftiger Gewächshäuser auf Planetenoberflächen und die damit verbundene Missionsplanung. Die Ergebnisse können aber auch die Zuverlässigkeit und Effizienz des Betriebs heutiger terrestrischer Lebensmittelproduktionssysteme (Gewächshäuser und Vertical Farms) verbessern, wodurch die Ergebnisse dort direkt anwendbar und relevant sind. Obwohl die Ergebnisse das begrenzte Forschungswissen über den Gewächshausbetrieb auf Planetenoberflächen und die dortige Anwendung von Augmented Reality erweitert haben, besteht in diesen Bereichen noch erheblicher Forschungsbedarf.

Publications

During my PhD studies, I (co-)authored five peer-reviewed publications, forming the basis of this thesis. Due to the topic of the dissertation and the related research questions, an interdisciplinary approach was chosen. Therefore, the research results obtained during this period have been published in space research and computer science journals and conferences. Publications 1 and 2 were published in a peer-reviewed space research journal. Publication 3 was published in a peer-reviewed space research conference. Publications 4 and 5 were published in peer-reviewed conferences focused on computer science. The numbering of publications 1 to 5 is based on the sequence in which they occur as chapters in the thesis. All publications were published in their final version, and my respective contributions are described in the following section. During my research career, I (co-)authored further publications related to space greenhouses. A list of these publications not related to this dissertation is provided at the end of this part of the thesis.

Publications included in this thesis:

Publication 1: *L. Poulet, C. Zeidler, J. Bunchek, P. Zabel, V. Vrakking, D. Schubert, G. Massa, and R. Wheeler, "Crew time in a space greenhouse using data from analog missions and Veggie," Life Sciences in Space Research, vol. 31, pp. 101–112, 2021, doi: 10.1016/j.lssr.2021.08.002.*

I contributed to structuring and writing the manuscript. Specifically, I was involved in developing a methodology for categorizing and reporting crew time in space greenhouses. I provided and reported the crew time data for the 2019 EDEN ISS season in Antarctica. Furthermore, I was involved in crew time predictions for various operation scenarios for future plant growth systems in the context of human exploration missions and discussions. I contributed to the revision of all manuscript sections for final publication [1].

Publication 2: *C. Zeidler, G. Woeckner, J. Schöning, V. Vrakking, P. Zabel, M. Dorn, D. Schubert, B. Steckelberg, and J. Stakemann, "Crew time and workload in the EDEN ISS greenhouse in Antarctica," Life Sciences in Space Research, vol. 31, pp. 131–149, 2021, doi: 10.1016/j.lssr.2021.06.003.*

During the 2019 EDEN ISS season in Antarctica, I was the primary person responsible for supporting the on-site operator team from the Mission Control Center in Germany, providing technical and horticultural support. I conceived and supervised the crew time, workload, and fresh edible biomass measurements originally included in this publication and conducted the analyses. In addition, I conducted the literature review and came up with the crew time categorization for remote support teams of space greenhouses. I drafted the manuscript and contributed to all sections of it. I revised the manuscript for final publication [2].

Publication 3: *C. Zeidler and J. Bunchek, "Workload measurements in the EDEN ISS greenhouse during the 2021 Antarctic overwintering mission," 52nd International Conference on Environmental Systems, 16-20 July 2023, Calgary, Alberta, Canada, 2023.*

I conceived and supervised the workload measurements originally included in this publication and conducted the analyses. I drafted the manuscript and contributed to all sections of it. I revised the manuscript for final publication [3].

Publication 4: *C. Zeidler, M. Klug, G. Woeckner, U. Clausen, and J. Schöning, "ARCHIE^2: An augmented reality interface with plant detection for future planetary surface greenhouses," in 2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), Sydney, Australia, 2023, pp. 601–610.*

I had the initial idea for the ARCHIE^2 augmented reality interface based on application areas that emerged from the experiences of the EDEN ISS space analog missions in Antarctica. I supervised and contributed to developing the ARCHIE^2 concept and developing, implementing, and testing its plant detection module. In addition, I contributed to the literature review as well as the analysis and discussion of the performance and perspective test results. I drafted the manuscript and contributed to all sections of it. I revised the manuscript for final publication [4].

Publication 5: *C. Zeidler, L. Kuhr, J. B. Callaham, and J. Schöning, "Mobile plant health visualizer based on SI-NDVI imaging and augmented reality visualization for space greenhouses," SpaceCHI 3.0: A Conference on Human-Computer Interaction for Space Exploration, 22-23 June 2023 at MIT Media Lab, 2023.*

I had the initial idea for the mobile plant health visualizer. I supervised and contributed to its development, implementation, and testing. In addition, I contributed to the analysis and interpretation of the testing results. I drafted the manuscript and contributed to all sections of it. I revised the manuscript for final publication [5].

Publications not included in this thesis:

Publication 6: *L. Poulet, D. Schubert, C. Zeidler, P. Zabel, V. Maiwald, E. David, and C. Paillé, "Greenhouse modules and regenerative life-support systems for space," in AIAA SPACE 2013 Conference and Exposition, San Diego, CA, 2013.*

Publication 7: *M. Bamsey, P. Zabel, C. Zeidler, L. Poulet, D. Schubert, E. Kohlberg, and T. Graham, "Design of a containerized greenhouse module for deployment to the Neumayer III Antarctic Station," 44th International Conference on Environmental Systems, 13-17 July 2014, Tucson, Arizona, USA, 2014.*

Publication 8: *P. Zabel, M. Bamsey, C. Zeidler, V. Vrakking, and B.-W. e. a. Johannes, "Introducing EDEN ISS - A European project on advancing plant cultivation technologies and operations," 45th International Conference on Environmental Systems, 12-16 July 2015, Washington, USA, 2015.*

Publication 9: *M. Bamsey, P. Zabel, C. Zeidler, D. Gyimesi, D. Schubert, E. Kohlberg, D. Mengedoht, and J. Rae, "Review of Antarctic greenhouses and plant production facilities: A historical account of food plants on the ice," 45th International Conference on Environmental Systems, 12-16 July 2015, Bellevue, Washington, USA, 2015.*

Publication 10: *V. Maiwald, D. Quantius, D. Schubert, P. Zabel, C. Zeidler, and V. Vrakking, "Glance into the future: research steps on a path to a continuous human presence on Moon, Mars and beyond," Acta Futura, vol. 10, pp. 45–59, 2016, doi: 10.5281/zenodo.202173.*

Publication 11: *M. Bamsey, P. Zabel, C. Zeidler, V. Vrakking, D. Schubert, E. Kohlberg, M. Stasiak, and T. Graham, "Early trade-offs and top-level design drivers for Antarctic greenhouses and plant production facilities," 46th International Conference on Environmental Systems, 10-14 July 2016, Vienna, Austria, 2016.*

Publication 12: *P. Zabel, M. Bamsey, C. Zeidler, V. Vrakking, D. Schubert, O. Romberg, G. Boscheri, and T. Dueck, "The preliminary design of the EDEN ISS Mobile Test Facility - An Antarctic greenhouse," 46th International Conference on Environmental Systems, 10-14 July 2016, Vienna, Austria, 2016.*

Publication 13: *C. Zeidler, V. Vrakking, M. Bamsey, L. Poulet, P. Zabel, D. Schubert, C. Paillé, E. Mazzoleni, and N. Domurath, "Greenhouse module for space system: A lunar greenhouse design," Open Agriculture, vol. 2, no. 1, pp. 116–132, 2017, doi: 10.1515/opag-2017-0011.*

Publication 14: *V. Vrakking, M. Bamsey, C. Zeidler, P. Zabel, D. Schubert, and O. Romberg, "Service Section design of the EDEN ISS project," 47th International Conference on Environmental Systems, 16-20 July 2017, Charleston, South Carolina, USA, 2017.*

Publication 15: *P. Zabel, M. Bamsey, C. Zeidler, V. Vrakking, D. Schubert, and O. Romberg, "Future Exploration Greenhouse design of the EDEN ISS project," 47th International Conference on Environmental Systems, 16-20 July 2017, Charleston, South Carolina, USA, 2017.*

Publication 16: *D. Schubert, M. Bamsey, P. Zabel, C. Zeidler, and V. Vrakking, "Status of the EDEN ISS greenhouse after on-site installation in Antarctica," 48th International Conference on Environmental Systems, 8-12 July 2018, Albuquerque, New Mexico, USA, 2018.*

Publication 17: *C. Zeidler, P. Zabel, V. Vrakking, M. Dorn, M. Bamsey, D. Schubert, A. Ceriello, R. Fortezza, D. de Simone, C. Stanghellini, F. Kempkes, E. Meinen, A. Mencarelli, G.-J. Swinkels, A.-L. Paul, and R. J. Ferl, "The plant health monitoring system of the EDEN ISS space greenhouse in Antarctica during the 2018 experiment phase," Frontiers in Plant Science, 10:1457, 2019, doi: 10.3389/fpls.2019.01457.*

Publication 18: *P. Zabel and C. Zeidler, "EDEN ISS: A plant cultivation technology for spaceflight," in Handbook of life support systems for spacecraft and extraterrestrial habitats, E. Seedhouse and D. J. Shayler, Eds.: Springer, Cham, 2019, pp. 1–15.*

Publication 19: *P. Zabel, C. Zeidler, V. Vrakking, M. Dorn, and D. Schubert, "Crewtime in a space greenhouse based on the operation of the EDEN ISS greenhouse in Antarctica," 49th International Conference on Environmental Systems, 7-11 July 2019, Boston, Massachusetts, USA, 2019.*

Publication 20: *P. Zabel, C. Zeidler, V. Vrakking, M. Dorn, and D. Schubert, "Biomass production of the EDEN ISS space greenhouse in Antarctica during the 2018 experiment phase," Frontiers in Plant Science, vol. 11, p. 656, 2020a, doi: 10.3389/fpls.2020.00656.*

Publication 21: *V. Maiwald, V. Vrakking, P. Zabel, D. Schubert, R. Waclavicek, M. Dorn, L. Fiore, B. Imhof, T. Rousek, V. Rossetti, and C. Zeidler, "From ice to space: a greenhouse design for Moon or Mars based on a prototype deployed in Antarctica," CEAS Space J, vol. 13, no. 1, pp. 17–37, 2021, doi: 10.1007/s12567-020-00318-4.*

Publication 22: *R. Fortezza, A. Ceriello, D. de Simone, D. Schubert, P. Zabel, C. Zeidler, and V. Vrakking, "The EDEN ISS facility as platform for plant experiments in extreme environments," Aerotec. Missili Spaz., vol. 99, no. 3, pp. 171–185, 2020, doi: 10.1007/s42496-020-00051-5.*

Publication 23: *R. Tucker, J. A. Callaham, C. Zeidler, A.-L. Paul, and R. J. Ferl, "NDVI imaging within space exploration plant growth modules – A case study from EDEN ISS Antarctica," Life Sciences in Space Research, vol. 26, pp. 1–9, 2020, doi: 10.1016/j.lssr.2020.03.006.*

Publication 24: *P. Zabel, C. Zeidler, V. Vrakking, and D. Schubert, "Implications of different plant cultivation techniques for food production in space based on experiments in EDEN ISS," International Conference on Environmental Systems, 2020.*

Publication 25: *C. Zeidler, V. Vrakking, P. Zabel, M. Bamsey, and D. Schubert, "Resource consumption and waste production of the EDEN ISS space greenhouse analogue during the 2018 experiment phase in Antarctica," International Conference on Environmental Systems, 2020.*

Publication 26: *V. Vrakking, C. Zeidler, P. Zabel, M. Dorn, and D. Schubert, "Status and future of the EDEN ISS Mobile Test Facility," International Conference on Environmental Systems, 2020.*

Publication 27: *P. Zabel, C. Zeidler, V. Vrakking, D. Schubert, B. Imhof, and M. Hogle, "Summary and evaluation of the EDEN ISS public outreach activities," International Conference on Environmental Systems, 2020.*

Publication 28: *C. Zeidler and G. Woeckner, "Using augmented reality in a planetary surface greenhouse for crew time optimization," ACM CHI 2021, SpaceCHI: Workshop on Human-Computer Interaction for Space Exploration, Virtual Conference, 14.05.2021, 2021.*

Publication 29: *S. Nesteruk, D. Shadrin, M. Pukalchik, A. Somov, C. Zeidler, P. Zabel, and D. Schubert, "Image compression and plants classification using machine learning in controlled-environment agriculture: Antarctic station use case," IEEE Sensors J., vol. 21, no. 16, pp. 17564–17572, 2021, doi: 10.1109/JSEN.2021.3050084.*

Publication 30: *P. Zabel, V. Vrakking, C. Zeidler, and D. Schubert, "Energy and power demand of food production in space based on results of the EDEN ISS Antarctic greenhouse," 51st International Conference on Environmental Systems, 10-14 July 2022, St. Paul, Minnesota, USA, 2022.*

Publication 31: *V. Maiwald, K. Kyunghwan, V. Vrakking, and C. Zeidler, "From Antarctic prototype to ground test demonstrator for a lunar greenhouse," Acta Astronautica, vol. 212, pp. 246–260, 2023, doi: 10.1016/j.actaastro.2023.08.012.*

Publication 32: *C. Zeidler, C. Patterson, M. Tremblay, M. Bamsey, and T. Graham, "Status and future of CSA's food production initiative - A strategic vision for Canada's future in lunar food production," 53rd International Conference on Environmental Systems, 21-25 July 2024, Louisville, Kentucky, USA, 2024. (in peer-review process, abstract accepted)*

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Chapter 1

Introduction

The final Apollo mission in 1972 marked the last time humans set foot on the Moon. Nearly 50 years later, as agreed in 2018 by 14 space agencies as part of the Global Exploration Roadmap [6], humanity now aims to return to the Moon by the end of the 2020s. The collective motivation is to conduct research and establish short-term infrastructure to test technologies needed for the next step in reaching Mars [7]. Long-term sustainable lunar habitats are planned for deployment in the mid-2030s [8]. Planetary surface greenhouses will be an essential component of such habitats on the Moon and Mars (Figure 1.1).

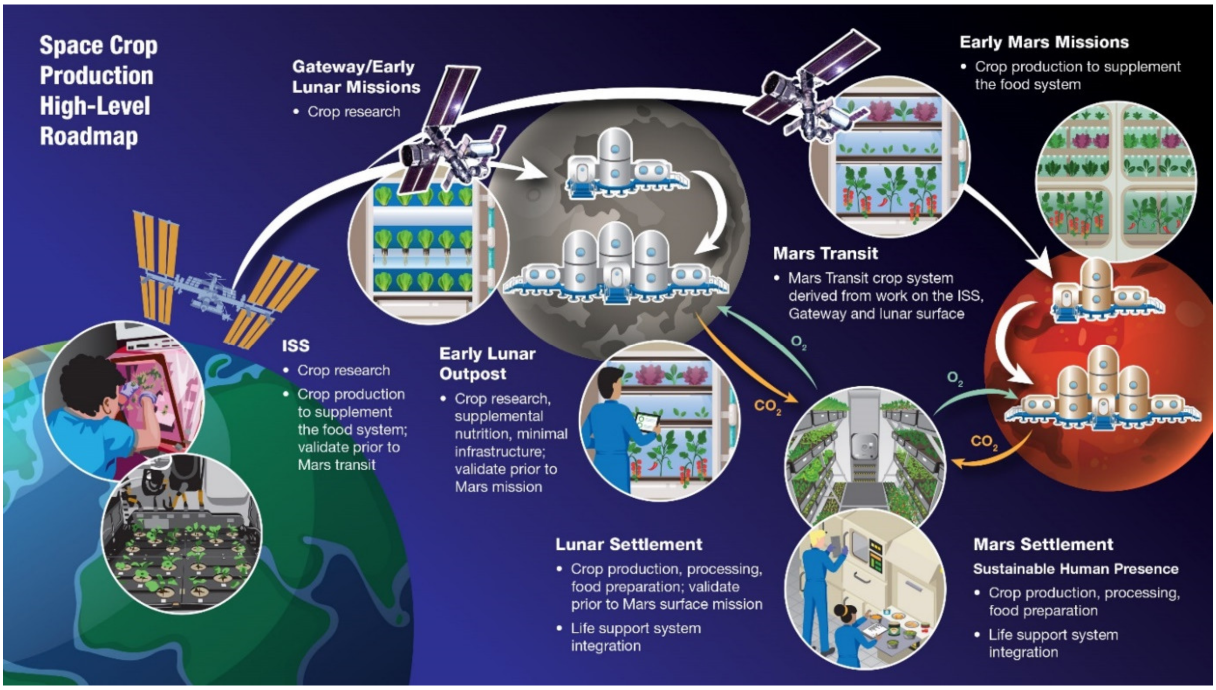


Figure 1.1: NASA's space crop production high-level roadmap toward Mars. [9]

These greenhouses will be required for food production and closure of material cycles through air processing and water recycling to reduce resource-intensive resupply from Earth [10], making lunar/Martian infrastructures more self-sufficient. Another important aspect of greenhouses is their potential to improve the psychological well-being of astronauts during space missions [11].

Astronauts will live on the Moon in an inhospitable environment characterized by high isolation, long lunar nights of up to 16 days (384 h) [12] depending on the location and mean temperatures at the equator of 122 K during lunar night [13] and 297 K during lunar day [13]. In addition, astronauts will live in highly engineered habitats that are entirely different from the accommodations on Earth. Bringing plants to the Moon and Mars could be beneficial for improving living conditions [14] and thus the psychological well-being of astronauts (Figure 1.2).

Figure 1.2: NASA astronauts Michael Hopkins and Shannon Walker enjoy the fresh scent of crops cultivated in the Veggie plant experiment hardware on the International Space Station. [15]

According to Schubert [16], it is planned that during early short-term missions, fast-growing pick-and-eat crops with high water content and low post-processing crew time demands will be grown, such as leafy greens, herbs, tomatoes, peppers, or microgreens [16]. As infrastructure expands and people stay on the Moon for extended periods, the variety of cultivated crops will be expanded to include those with higher nutrient density and potentially higher post-processing crew time demands [16]. These long-duration candidate crops will likely include peanuts, potatoes, rice, soybeans, or bread wheat [16]. Regardless of the crop selection, research must be done to optimize resource use efficiency, including crew time.

Before space missions can be realized, the technologies used and their operations must be tested and refined on Earth. These preparatory activities can be performed in laboratories under space-like conditions and in analog test sites. Analog test sites are particularly used to test operations, procedures, and technologies for space missions under more realistic conditions similar to those on the Moon or Mars [17]. Analog conditions include isolation, habitat and technology dependence of the crew, crew size, low biodiversity, harsh environment, resupply and communication capabilities, or geological conditions of the surroundings [17, 18]. The selection of a specific analog test site depends on the planned space mission for which the tests are to be conducted but also on the available budget and schedule of a mission [17].

Examples of analog test sites [17, 19] include deserts (e.g., Utah Mars Desert Research Station (MDRS) [20, 21], Desert Research and Technology Studies (Desert RATS) [22]), volcanoes/mountains (e.g., Hawaii Space Exploration Analog and Simulation (HI-SEAS) on the Mauna Loa volcano in Hawaii [23, 24]), caves [25, 26], underwater sites (e.g., Aquarius Underwater Laboratory used for the NASA Extreme Environment Mission Operations (NEEMO) in the Florida Keys National Marine Sanctuary [27]), other facilities for isolation studies (e.g., Mars-500 [28], Lunar Palace [29], BIOS-3 [30, 31]), or sites in the Arctic (e.g., Arthur Clarke Mars Greenhouse located in the Canadian High Arctic [32]), and Antarctica (e.g., South Pole Food Growth Chamber (SPFGC) [33]).

The EDEN ISS project of the German Aerospace Center (DLR) also used Antarctica as an analog test site from 2018 to 2022 to test and refine critical technologies and operations for planetary surface greenhouses under space analog conditions in a greenhouse facility called the Mobile Test Facility (MTF) [34, 35]. The greenhouse was located 400 m south of the polar research station Neumayer Station III (NM III), operated by the Alfred Wegener Institute for Polar and Marine Research (AWI) [36, 37]. During four one-year analog missions, the greenhouse produced 1,017 kg of edible fresh biomass on a 12.5 m^2 growth area, cultivating crops such as lettuces, leafy greens, herbs, tubers, and fruit-bearing crops such as tomatoes, cucumbers, and peppers [2, 3, 38, 39].

1.1 Motivation and Problem

In spaceflight, crew time is a valuable but limited resource [40–42] and is therefore scheduled on the International Space Station (ISS) with an accuracy of five-minute increments [43]. A significant amount of crew time is spent on maintenance and repairs onboard the ISS [44, 45]. As the success of the mission and the lives of the astronauts depend on these tasks, they are prioritized over other activities, such as conducting science [40, 45, 46]. For this reason, overall crew time needs to be minimized as much as possible to allow more time for scientific activities. Similar trends apply to space greenhouses [32, 47, 48].

To reduce crew time for the on-site operators (astronauts) and the remote support teams (RST) in the Mission Control Center (MCC) on Earth, starting points must be identified to optimize the planning processes for future space mission scenarios, the design of space greenhouse systems, and their operations. For this purpose, the identification of allocated crew time values for various greenhouse operations is of crucial importance. These values form the basis for determining the feasibility of such missions and for ensuring reliable and efficient workflows, enabling an optimal allocation of scientific and non-scientific activities. For example, Russell *et al.* [45] reported that the planned crew time was less than the actual crew time on these missions. This deviation was caused by underestimating maintenance and repair activities at the expense of other activities, which consequently could compromise the outcome of the space mission [45].

Another crucial aspect to consider when planning future space missions and associated space greenhouse activities is the perceived workload during these missions. Negatively perceived tasks should be automated as much as possible to improve the astronaut's psychological well-being, which is another factor critical to mission success. To take advantage of plant cultivation's positive contributions to the crew's psychological well-being, tasks perceived as positive should not all be automated. Which activities are perceived as positive or negative depends on the astronauts' individual preferences.

However, the literature review showed that insufficient data on crew time and workload demand is publicly available and that the published crew time values are difficult to compare because there is no standardized method for measuring crew time.

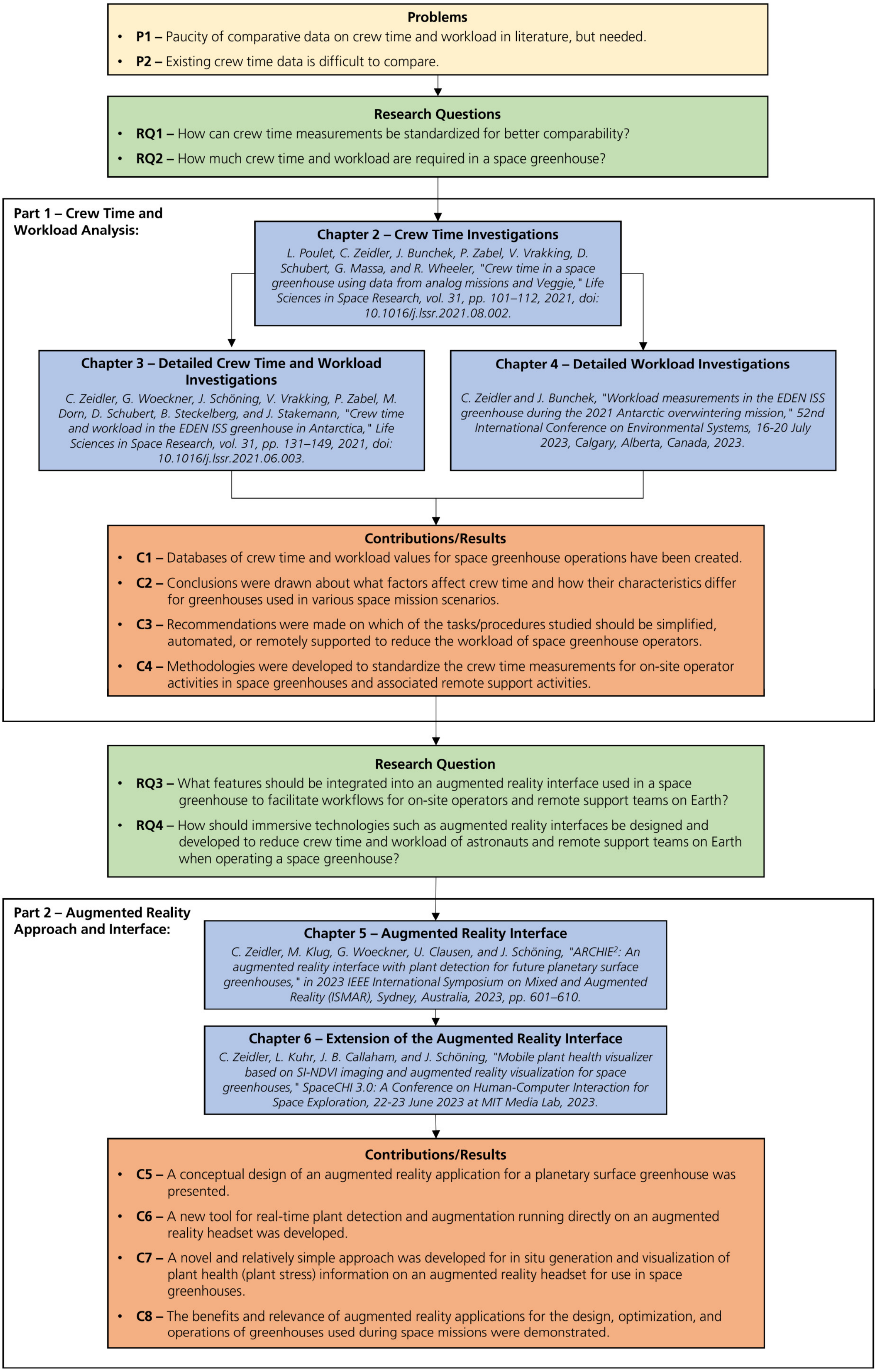
This results in the challenges summarized in the following problems (**P**), which are the starting point of this thesis:

P1 There is a lack of comparative data on crew time and workload in the literature. However, such data are urgently needed for planning future space missions and designing space greenhouses.

P2 Existing crew time data is difficult to compare because there is no consistent methodology for measurement and categorization.

1.2 Contributions and Thesis Outline

The thesis is divided into two parts (Figure 1.3), with the first part focusing primarily on space-related research questions, analyzing crew time and workload in space greenhouses. In order to define the topics of the second part of the thesis, it was first necessary to address problems **P1** and **P2** originated from the field of space exploration, as addressing them revealed the possibility of using augmented reality (AR) [49–52] to solve a space research-related challenge. Therefore, the second part of the thesis deals more with computer science-related research questions, analyzing an AR approach for use in greenhouses for the Moon and Mars. This interaction between computer science and space-related research necessitated an interdisciplinary approach, which will be explained in more detail below.



Problems

- **P1 –** Paucity of comparative data on crew time and workload in literature, but needed.
- **P2 –** Existing crew time data is difficult to compare.

Research Questions

- **RQ1 –** How can crew time measurements be standardized for better comparability?
- **RQ2 –** How much crew time and workload are required in a space greenhouse?

Part 1 – Crew Time and Workload Analysis:

Chapter 2 – Crew Time Investigations

L. Poulet, C. Zeidler, J. Bunchek, P. Zabel, V. Vrakking, D. Schubert, G. Massa, and R. Wheeler, "Crew time in a space greenhouse using data from analog missions and Veggie," Life Sciences in Space Research, vol. 31, pp. 101–112, 2021, doi: 10.1016/j.lssr.2021.08.002.

Chapter 3 – Detailed Crew Time and Workload Investigations

C. Zeidler, G. Woeckner, J. Schöning, V. Vrakking, P. Zabel, M. Dorn, D. Schubert, B. Steckelberg, and J. Stakemann, "Crew time and workload in the EDEN ISS greenhouse in Antarctica," Life Sciences in Space Research, vol. 31, pp. 131–149, 2021, doi: 10.1016/j.lssr.2021.06.003.

Chapter 4 – Detailed Workload Investigations

C. Zeidler and J. Bunchek, "Workload measurements in the EDEN ISS greenhouse during the 2021 Antarctic overwintering mission," 52nd International Conference on Environmental Systems, 16-20 July 2023, Calgary, Alberta, Canada, 2023.

Contributions/Results

- **C1 –** Databases of crew time and workload values for space greenhouse operations have been created.
- **C2 –** Conclusions were drawn about what factors affect crew time and how their characteristics differ for greenhouses used in various space mission scenarios.
- **C3 –** Recommendations were made on which of the tasks/procedures studied should be simplified, automated, or remotely supported to reduce the workload of space greenhouse operators.
- **C4 –** Methodologies were developed to standardize the crew time measurements for on-site operator activities in space greenhouses and associated remote support activities.

Research Question

- **RQ3 –** What features should be integrated into an augmented reality interface used in a space greenhouse to facilitate workflows for on-site operators and remote support teams on Earth?
- **RQ4** – How should immersive technologies such as augmented reality interfaces be designed and developed to reduce crew time and workload of astronauts and remote support teams on Earth when operating a space greenhouse?

Part 2 – Augmented Reality Approach and Interface:

Chapter 5 – Augmented Reality Interface

C. Zeidler, M. Klug, G. Woeckner, U. Clausen, and J. Schöning, "ARCHIE²: An augmented reality interface with plant detection for future planetary surface greenhouses," in 2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), Sydney, Australia, 2023, pp. 601–610.

Chapter 6 – Extension of the Augmented Reality Interface

C. Zeidler, L. Kuhr, J. B. Callaham, and J. Schöning, "Mobile plant health visualizer based on SI-NDVI imaging and augmented reality visualization for space greenhouses," SpaceCHI 3.0: A Conference on Human-Computer Interaction for Space Exploration, 22-23 June 2023 at MIT Media Lab, 2023.

Contributions/Results

- **C5 –** A conceptual design of an augmented reality application for a planetary surface greenhouse was presented.
- **C6 –** A new tool for real-time plant detection and augmentation running directly on an augmented reality headset was developed.
- **C7 –** A novel and relatively simple approach was developed for in situ generation and visualization of plant health (plant stress) information on an augmented reality headset for use in space greenhouses.
- **C8 –** The benefits and relevance of augmented reality applications for the design, optimization, and operations of greenhouses used during space missions were demonstrated.

Figure 1.3: Contributions and thesis outline. P = problem; RQ = research question; C = contribution.

1.2.1 Crew Time and Workload Analysis

Based on the problems **P1** and **P2**, identified in the challenges of the previous subsection, the following research questions (**RQ**) emerged (Figure 1.3), which were used as baseline questions for the first part of this thesis (Chapters 2 to 4) [1–3]:

RQ1 How can crew time measurements be standardized for better comparability?

RQ2 How much crew time and workload are required in a space greenhouse?

To answer **RQ1** and **RQ2**, the required crew time for greenhouse operations in space analog facilities such as EDEN ISS, MDRS, HI-SEAS, the Inflatable Lunar/Mars Habitat (ILMAH), and the Veggie plant experiment hardware on the ISS were investigated and analyzed in the publication that forms the basis for Chapter 2.

Additional detailed crew time and workload measurements were performed to substantiate further the fundamentals (Chapters 3 and 4). Crew time was measured for various groups (on-site operator and RST in the MCC) involved in greenhouse operations. Measurements were taken for various operational tasks of a space analog mission to create weekly and monthly crew time demand profiles and to relate the crew time of the on-site operator team (OOT) and the RST (Chapter 3).

To complement the crew time measurements, workload measurements for full mission phases of a space analog mission were conducted using the NASA Task Load Index (TLX) questionnaire [53–56] for specific groups involved, such as the OOTs, on-site summer maintenance teams (SMT), and RSTs. In addition, the on-site operator workload was measured for specific recurring tasks/procedures, such as daily/weekly/monthly routines, pruning, and pruning, as well as daily, weekly, and monthly workload to assess how workload changes throughout the mission (Chapters 3 and 4).

This resulted in the first contributions (**C**) of this thesis regarding **RQ1** and **RQ2** (Figure 1.3):

C1 Databases of crew time and workload values for space greenhouse operations have been created based on various crew time and workload studies (Chapters 2 to 4). These studies have shown the need to reduce crew time and workload of the people involved in operating space analog greenhouses (remote and on-site). These findings have implications for future greenhouse operations on the Moon and Mars, where crew time must be optimized to conduct more science activities [7]. These databases also support the planning processes for future space missions, greenhouse operations, and greenhouse designs.

C2 Conclusions were drawn about which factors affect crew time and how their characteristics differ for greenhouses used in various space mission scenarios, such as space stations, interplanetary travel, and planetary surfaces (Chapter 2). These factors are the type of crops chosen, choices for watering systems, health and environmental monitoring systems, sowing and harvesting methods, operations training, management of cleaning operations and consumables, maintenance, dormancy, new hardware, number of operators, level of automation, and crew time available for plant care. In addition, assumptions required to predict crew time for greenhouse activities in the three scenarios were described in detail.

C3 Recommendations were made for the design and planning processes of future lunar and Martian space greenhouses on which of the greenhouse tasks/procedures studied should be simplified (e.g., using virtual reality (VR) or AR), automated (e.g., using robotics), or remotely supported to reduce the workload of greenhouse operators (Chapter 4). The tasks that showed the most significant potential for reducing workload due to their high workload demand measured were greenhouse system cleaning, nutrient solution preparation, plant monitoring, seeding, and harvesting. Activities such as data analysis and sampling for scientific purposes also have the potential to reduce workload if automated or performed in a simplified way. Furthermore, it is critical to account for off-nominal events (e.g., equipment failures) during the planning and actual mission phases and to plan all outreach activities well in advance with support from MCC. For all activities performed in a space greenhouse, setting achievable goals for the on-site operators to reduce their workload is crucial.

C4 Based on the crew time measurements, methodologies were developed to standardize the crew time measurements for on-site operator activities in space greenhouses (Chapter 2) and associated remote support activities (Chapter 3) to increase comparability of crew time values and facilitate its analysis. On-site operator crew time measurements should be conducted during a representative period for plant growth-related tasks subdivided into activities such as plant ops (sub-activities health monitoring, cultivation ops, and harvest processing), upkeep ops (sub-activities routine ops and maintenance), utilization, work prep, public relations, conference (entire crew), tag-ups (individual), and personal time. This categorization is based on the crew time ontology of non-plant cultivation-related tasks presented by Stromgren *et al.* [41]. On the other hand, remote support crew time values should be measured for six generic categories identified during the 2019 EDEN ISS mission, such as nominal meetings, housekeeping, nominal support, off-nominal support, organization next mission, and science support. The categories are based on the scope of work, the task type, and whether the task is planned or unplanned. These categorizations will help to better analyze, understand, and visualize the crew time measurements for space greenhouses.

1.2.2 Augmented Reality Approach and Interface

An important research question from the EDEN ISS analog missions was how to optimize operations in future planetary surface greenhouses [57]. Based on the findings of the EDEN ISS analog missions and the contributions **C1** to **C3**, options to facilitate operations were investigated.

To reduce crew time, maintenance and repair activities must be performed quickly, effectively, efficiently, and safely without error. This allows more time for other activities during a space mission, such as scientific research. In recent years, AR has gained importance in optimizing workflows in various application fields, including medicine [58–61], the aerospace industry [61–63], education/training [58, 61, 64], livestock farming [65–67], navigation/tourism [58, 61, 62], and the gaming industry [58, 61]. Space applications have also been investigated regarding facilitating astronaut workflows during space missions using AR systems, such as Wireless Augmented Reality Prototype (WARP) [68, 69], Wearable Augmented Reality (WEAR) [70, 71], mobile Procedure Viewer (mobiPV) [72–74], Engineering data in cross-platform Augmented Reality (EdcAR) [75], Sidekick [76, 77], T2 Augmented Reality (T2AR) [77–79], Augmented Reality Guidance and Operations System (ARGOS) [80], Joint Augmented Reality Visual Informatics System (Joint AR) [81], and Augmented Lunar Exploration and Extravehicular Interface (ALEXEI) [82]. AR applications can also be used to support the operations of future greenhouses on the Moon and Mars. However, there is still a great need for research in AR applications for the agricultural context on Earth [83, 84], and there are hardly any applications for greenhouses in space.

For this reason, in the second part (Chapters 5 and 6) [4, 5] of this thesis, the application potential of AR in future greenhouses on the Moon and Mars was investigated as an option to support the performance of various plant cultivation tasks, to reduce crew time and workload. This approach attempts to solve a problem that originated in space exploration research by applying computer science in an interdisciplinary way.

Computer science research has shown that by using AR and augmenting the user's field of view through interactive virtual elements, errors in task execution can be reduced [85, 86], and compliance with procedures increased [86]. This can increase the accuracy [72, 86] and efficiency of users when performing tasks [72], as fewer errors and delays occur [85, 86]. In addition, the use of AR headsets can enable hands-free operations without the need to type or use paper documents [70, 72, 86].

These benefits could also apply to AR applications used in space greenhouses as they could reduce existing challenges. They could reduce crew time [72, 85, 86] and workload [85] of the greenhouse on-site operators and the RSTs on Earth. In addition, a higher autonomy level [86] of the on-site operators from Earth support could be achieved by using AR, which is highly relevant for missions beyond low Earth orbit (LEO), such as Mars missions, where a remote support reduction is likely due to communication delays and costs [73]. Moreover, AR could be used to reduce the training processes and needs [86] for on-site operators in space greenhouses and to counteract the knowledge loss caused by the gap of several months [87] between training and the actual space mission.

Thus, the research questions underlying the second part of this thesis can be formulated as follows (Figure 1.3):

RQ3 What features should be integrated into an AR interface used in a space greenhouse to facilitate workflows for on-site operators and RSTs on Earth?

RQ4 How should immersive technologies such as AR interfaces be designed and developed to reduce crew time and workload of astronauts and RSTs on Earth when operating a planetary surface greenhouse?

To answer **RQ3** and **RQ4**, the use of AR was investigated in the publications that form the basis for Chapters 5 and 6. A first concept of an AR interface called ARCHIE^2 (Augmented Reality Computer-Human Interface for grEEnhouses) was developed for use on an AR headset, which can facilitate operations in a planetary surface greenhouse by displaying information such as status information on plants, technical systems, and environmental parameters in the greenhouse as well as greenhouse related procedures (Chapter 5). As hands-free operations and mobility are advantages for on-site operators in space greenhouses, the decision was made to use an AR headset rather than an AR handheld device such as a tablet. The Analytic Hierarchy Process (AHP) [88–90] was used by Woeckner [91] to compare and evaluate eleven AR headsets available on the market. The Microsoft HoloLens 2 was found to meet best the requirements for use in a space greenhouse regarding hardware specifications, form factor and weight, ocularity, field of view, user interfaces, display resolution and technology, development platforms, sensors, battery life, and durability [91]. It was used for all practical AR applications in the second part of this thesis.

Individual features of the ARCHIE^2 AR interface were implemented, and the application's performance was investigated (Chapter 5). A plant detection system was implemented locally on an AR headset and based on this, plants were virtually augmented with labels to visualize relevant plant-specific information.

The use of plant health monitoring (PHM) techniques is of great importance for optimizing crop cultivation [92], and is largely realized using Single-Image Normalized Difference Vegetation Index (SI-NDVI) imaging to detect plant stress prior to visual appearance [93]. Currently, this technique is implemented in greenhouses using multiple statically mounted imagers [94, 95] or expensive robotic systems, increasing the cost and complexity of such systems.

For this reason, a plant stress detection application using SI-NDVI imaging was added to the ARCHIE² AR interface and its performance was investigated during a salinity stress test of Orange Cherry tomato (*Solanum lysopersicum* cv. 'Nugget') plants (Chapter 6). With this novel approach using an AR interface, the user receives real-time plant health information (plant stress information) displayed in situ as a false color hologram based on SI-NDVI measurements. No additional cameras are needed, which reduces the cost and complexity of a PHM system and facilitates integration within various setups.

RQ3 and **RQ4** formed the basis for the second part of the thesis contributions (Figure 1.3):

C5 A (first) conceptual design of an AR application called ARCHIE² for a planetary surface greenhouse was presented (Chapter 5). Various AR features are discussed, such as visualizing information on technical systems, environmental parameters or plants, and other functions to support operational tasks in a space greenhouse. The aim is to facilitate workflows of OOTs and RSTs on Earth and ultimately reduce workload and crew time through the previously mentioned AR benefits. The knowledge gained adds to the limited research in this area and may serve as a benchmark for future research.

C6 A new tool for real-time plant detection and augmentation running directly on an AR headset was developed (Chapter 5). To support the user's operational tasks in the greenhouse, plant-specific information is displayed on virtual labels close to the detected plants, preventing the labels from being obscured. The prototype was trained to detect arugula selvatica but can be trained to detect other plant species in the same way using the methods described in this thesis. However, this requires further annotated datasets of other plant species currently scarce in the agricultural context. Automated plant detection is also crucial for plant cultivation systems using plant-tending robots to reduce the on-site operator workload in space greenhouses. The results presented on the performance and implementation of the plant detection and augmentation process also provide important benchmarks for research in this area and are applicable for both space and terrestrial greenhouses.

C7 A novel and relatively simple approach was developed for use in space greenhouses to generate and visualize plant health information (plant stress) in situ on an AR headset using SI-NDVI imaging (Chapter 6). The approach was validated on a mobile plant health visualizer (MPHV) prototype that qualitatively visualizes plant stress responses in AR. The MPHV can increase the autonomy of the OOTs from RSTs on the ground, as plant stress responses can be detected and addressed in real-time, even before visible plant symptoms appear. Furthermore, the mobile nature of the system increases user flexibility as plants can be inspected anywhere in the cultivation area with relatively low system complexity and cost. By providing information on the implementation and performance of the PHM system, benchmarks are provided for future studies. In addition to space applications, this system is also relevant to terrestrial applications.

C8 The benefits and relevance of AR applications in developing, optimizing, and operating greenhouse systems used in space missions have been demonstrated, which could also have positive implications for terrestrial applications (Chapters 5 and 6). However, more research is needed, such as further user studies under space analog conditions to validate the performance and usability of AR applications for space greenhouse operations.

Chapter 7 summarizes the thesis results concerning research questions **RQ1** to **RQ4** and outlines how each chapter contributes to the key contributions of this thesis. Finally, the planned future work is described, including expected results and implications, and recommendations are made for research gaps that require further investigations.

Chapter 2

Crew Time Investigations

Life Sciences in Space Research

Crew time in a space greenhouse using data from analog missions and Veggie

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ARTICLE INFO

ABSTRACT

Chapter 2 directly addresses the research questions **RQ1** and **RQ2** underlying the first part of this thesis. To expand the limited existing database of crew time values of past analog and space missions for crop cultivation, we analyzed and compared the crew time data from space analog facilities such as EDEN ISS, MDRS, HI-SEAS, and ILMAH as well as the Veggie plant experiment hardware on the ISS (**C1**).

Through the analysis of the database created, a standardized methodology for measuring crew time of on-site operators in space greenhouses was developed, improving the assessability and comparability of crew time requirements (**C4**). Furthermore, the factors affecting crew time for future greenhouse operations for various space mission scenarios, such as on space stations, during interplanetary travel, and on planetary surfaces, were investigated and assumptions were made to improve the associated crew time estimates (**C2**).

The analysis showed that crew time for space greenhouse operations is a valuable resource, and its allotment needs to be optimized during future space missions. The research presented provides valuable insights for mission planners and space greenhouse designers to consider when preparing plant cultivation procedures, designing plant cultivation systems, or planning scientific activities.

The information presented in this chapter was originally published in *L. Poulet, C. Zeidler, J. Bunchek, P. Zabel, V. Vrakking, D. Schubert, G. Massa, and R. Wheeler, "Crew time in a space greenhouse using data from analog missions and Veggie," Life Sciences in Space Research, vol. 31, pp. 101–112, 2021, doi: 10.1016/j.lssr.2021.08.002.*

2.1 Introduction

2.1.1 Context

Crew time in space is precious and expensive – one hour of crew time for commercial or marketing activities currently costs \$130,000 [42] – but it is a crucial human spaceflight parameter for efficient mission planning [45, 96]. For instance, crew time analysis revealed that crew time prediction for the environmental control and life-support system (ECLSS) maintenance on the ISS during the design phase was underestimated by an order of magnitude [45]. The astronauts' schedules on ISS are currently planned with a precision of five-minute increments [43]; the station's 20 years of existence have allowed for collecting invaluable data on required time for each activity and drawing predictions for future Mars missions [41, 46]. Mattfeld *et al.* [46] estimated that a crew on Mars would need to dedicate 2 h week^{-1} per crew member for food preparation, against 3.25 h week^{-1} per crew member on ISS (2007 to 2013) [46]. These predictions are based on the assumption that meals would be meals ready to eat (MRE), so they do not include time needed to tend plants and crop cultivation for food production. However, current prepackaged foods degrade with storage duration, which leads to inadequate nutrition [97]. Given this, when considering long-duration human exploration missions, plants may need to be included to improve crew's nutrition, limit resupply mass, and increase missions sustainability [10, 98].

There are currently two NASA crop cultivation systems on the ISS: Veggie and the Advanced Plant Habitat (APH) [99]. Veggie has been operational since 2014 [100] – with one Veggie unit, followed in 2017 by a second one – and the first experiment in APH occurred in 2018 [101]. Crew time for initiation, watering, photos, and harvesting in Veggie is routinely recorded, but this is the first time it is reported in a scientific article [1]. This article is the basis for this chapter.

To our knowledge, crew time dedicated to plant growth in a Moon/Mars analog facility was reported in the academic literature for only two different analog habitats, the HI-SEAS during the second mission [23] and the MDRS during Missions 135, 139, and 140 [20], but this is the first time data are presented in the context of an overview of crew time expectations for crop production as it relates to life-support. During HI-SEAS II, average daily crew time to tend plants was 15.6 min for a plant growth area of approximately 0.5 m^2, which translates to 31.2 min day^{-1} m^{-2}. This included daily watering, health and temperature checks, plant cultivation activities such as sowing and harvesting, and preventive maintenance and routine operation activities such as systems cleaning and mixing nutrient solution. Throughout MDRS Missions 135, 139, and 140, average daily crew time was approximately 45 min for 5 m^2 plant growth area, i.e., 9 min day^{-1} m^{-2}, which consisted of similar activities as in HI-SEAS II, plus site-specific tasks such as setting up insect traps or replacing hydroponics solution.

During the Russian experiment BIOS-3, about 16 min day^{-1} m^{-2} of crew time was needed [47, 102] to maintain 34 m^2 of wheat and 3.5 m^2 of miscellaneous vegetables. The most time-consuming task was wheat grinding with about 8 min day^{-1} m^{-2}; the rest of the activities consisted of planting, harvesting, observation, preventive maintenance, and hydroponic nutrient solution maintenance [47, 102], which is comparable (except for wheat grinding) to the two previously cited analog missions.

Patterson *et al.* reported in [33] that 23 h $week^{-1}$ were needed to operate the 22.8 m^2 plant cultivation area in the US Amundsen Scott South Pole Station's greenhouse, a crew time of 9 min day^{-1} m^{-2} of growing area, excluding repair and maintenance of main hardware [33]. The growing area of the DLR EDEN ISS greenhouse (12.5 m^2), in the vicinity of the German NM III, is about half that of Amundsen-Scott Station, but the diversity of plants grown in EDEN ISS is much larger [38, 48]. For the 2018 season, the EDEN ISS operator spent an average of 3 h day^{-1} for system maintenance and plant care. Additional time was needed to don protective winter clothing and walk to and from the greenhouse module. The remaining time was used to take samples and measurements and to run experiments. Crew time for maintenance was about 88 min $month^{-1}$ m^{-2} of growing area, i.e., 2.93 min day^{-1} m^{-2} of growing area [48]. Instead of presenting the overall amount of crew time needed to operate the greenhouse, the team reported the amount of crew time per day needed for each crop per unit of growing area and per kg. This provides greater insight into the greenhouse operations and flexibility for future predictions, as it identifies crew time-intensive crops.

2.1.2 Objectives of the Current Study

This chapter summarizes the results of a retrospective study on crew time data collected in various analogs and in Veggie on ISS between 2014 and 2019. The objectives of this chapter are to (1) propose a methodology for efficient crew time reporting in space plant growth systems, (2) provide a crew time database for existing plant growth hardware on ISS and in different analog facilities and research stations on Earth, and (3) use these data to pinpoint factors that influence crew time and predict how it might change in future interplanetary and planetary plant growth facilities. Of course, ISS and these Earth facilities are not direct analogs for future plant growth hardware for missions to the Moon and Mars (on the surface and in the vicinity). Crew time will vary significantly depending on mission scenario, greenhouse module size, level of automation, and crew size, and may also vary by the amount of gravity. However, defining required tasks for plant growth and associated crew time per m^2 in long-duration analogs and on ISS, as well as identifying main maintenance and repair events and their recurrence, can serve as a baseline to establish standardized activities and associated crew time. This can be used to extrapolate required crew time for specific tasks on future exploration missions and be used by mission planners.

The materials and methods section details the facilities and plant hardware for which crew time was recorded and the associated collection method. In the results section, daily crew time is reported for each facility and categorized into different activities, and influencing factors and assumptions about crew time needed for future space plant growth hardware are detailed. The last section discusses crew time reporting, its importance in system design, and the case for developing a standardized method.

2.2 Materials and Methods

2.2.1 Crew Time Categorization

Stromgren *et al.* [41] defined a standardized crew time ontology based on ISS activity categorization [41]. Plant Care was not an identified activity, so we have defined new categories and activities, based on the four items identified by the DLR EDEN ISS team: crop cultivation, maintenance, repair, and science [48]. This is summarized in Table 2.1, where text in *italic* refers to already existing items, as defined by Stromgren *et al.* [41].

The use of Table 2.1 for crew time reporting in space and analog plant growth systems is the first step in the methodology we propose in Subsection 2.4.3. We added the column "Unit Operations" to further divide tasks and to enable flexibility for different system designs. This column is populated here to give examples – some cells are empty because the systems on which we report did not have relevant examples. The "Health Monitoring" sub-activity only encompasses the action of monitoring, not the actions to adjust plant health. This is counted under "Corrective treatments" within the "Cultivation Ops" sub-activity. Hardware adjustments are counted under "Corrective repair", within the "Maintenance" sub-activity.

Table 2.1: Subdivision of plant growth-related tasks for crew time recording. This is adapted from Stromgren et al. [41] and follows their crew time ontology. [a] The information in these cells was updated due to a processing error in Poulet et al. [1]. Temp. = temperature; RH = relative humidity; nb. = number.

Category	Sub-Category	Activity	Sub-Activity	Operation Type	Unit Operation
Work	*Scheduled Operations*	Plant Ops	Health Monitoring	Environment	Temp., RH, CO_2, g (per task)
				Crops	Disease, pathogens (per task)
			Cultivation Ops	Starting	Sowing (per m^2, per seed nb.)
					Initiation (per m^2)
				Adjusting	Thinning (per m^2)
					Reorganization (per m^2)
					Pruning (per m^2)
					Trellising (per m^2)
				Enhancing	Pollination (per m^2)
					Fertilizing (per m^2)
				Harvesting	Leaves cutting (per m^2)
				Corrective treatments	Nutrient addition (per m^2)
				Manual watering	Using a syringe (per m^2)
			Harvest processing	Food quality and safety monitoring	Elemental analysis (per m^2)
					Microbiology (per m^2)
				Edible biomass processing	Washing (depends on species)
					Grinding (per kg)
					Milling (per kg)
					Packaging (per kg)
					Storing (per kg)
		Upkeep Ops	*Routine Ops*	Operations training [a]	Harvest procedure (per task)
				Subsystem checks [a]	HVAC (per task)
				Routine adjustments [a]	Cultivation variables (per task)
				Nutrient solution mixing	(per task)
				Consumables management	(per task)
				Hardware/Facility cleaning	Growth area cleaning (per m^2)
					Work area cleaning (per task)
				Water management	Waste water (per task)
					Fresh water (per task)
			Maintenance	*Corrective repair*	Equipment repair (per task)
				Corrective adjustments	Cultivation variables (per task)
				Scheduled preventive	(per task)
		Utilization		Plant data collection	Photos (per task)
				System data collection	Logs (per task)
	Ops Prep and Conference	*Work Prep*		Greenhouse access	Donning/Doffing suits
					Walking to greenhouse
				Hardware set-up	Hardware install (per task)
		Public Relations		Media interviews	TV, radio (per task)
				Public outreach	Schools (per task)
		Conference (entire crew)			(per task)
		Tag-Ups (individual)			(per task)
Non-Work		*Personal*	Leisure time	Relaxing in greenhouse module	Reading (per task)
					Sleeping (per task)
					Dining (per task)
				Sensory experience with plants	Looking (per task)
					Smelling (per task)
					Artistic photos (per task)
					Drawing (per task)
					Touching (per task)

2.2.2 Veggie

Hardware Overview

There are currently two Veggie units on ISS: one since 2014, the other since 2017. Each unit consists of six plant-growing pillows where the seeds have been pre-sown on Earth prior to launch (though astronaut installation of seed insertion is being tested), a red-blue-green (RGB) LED system, a fan, and bellows walls to partially isolate the unit from the rest of the cabin and to ensure ventilation throughout the canopy and some uniformity in growing conditions. Crew members manually water plant pillows using syringes and perform harvests by cutting leaves with dedicated scissors. Half of the harvest is consumed by the crew, and the other half is stored in one of the on-board freezers (MELFI or MERLIN) [103] and sent back to Earth for analysis.

Data Collection Method

Data presented in this chapter were collected from 13 experiments between July 2014 and December 2019, which lasted approximately one month (33 days for VEG-01 A and VEG-01B; 28 days for VEG-03B and VEG-03H; 34 days for VEG-03G; and 35 days for VEG-04 A), approximately two months (64 days for VEG-03 A; 58 days for VEG-03C, VEG-03D, and VEG-04B; and 59 days for VEG-03E and VEG-03F), and 90 days (VEG-01C) [100]. The one-month studies were single-harvest experiments where plants were grown and harvested simultaneously. Longer experiments featured cut-and-come-again harvests, with multiple harvests performed on the same plants throughout the studies. Crew time data were retrieved from ISS crew scheduling software for the corresponding payloads and normalized to one Veggie unit (for the experiments using both Veggie units). Activities pertaining to Veggie were logged within five-minute increments and described according to the tasks performed, such as daily checks (plant health and environment), watering, photos, and harvest.

2.2.3 EDEN ISS

Hardware and Mission Overview

The MTF of the EDEN ISS project (Figure 2.1) is located 400 m south of the German NM III in Antarctica (70°40'S, 8°16'W). The station is operated by the AWI and serves as a testbed for space analog missions. The MTF was built by an international consortium led by the DLR in the frame of the European Union Horizon 2020 program (reference number: 636501), supported via the COMPET-07-2014 – Space exploration – Life-support subprogram, with the goal to validate key technologies for space greenhouses under mission analog conditions and with representative mass flows [34, 35].

Figure 2.1: View of the EDEN ISS Future Exploration Greenhouse in Antarctica with the Neumayer Station III in the background. Photo credits: Paul Zabel.

The MTF can be subdivided into three distinct sections:

- Cold porch/airlock (CPO): a small room providing storage and a small air buffer to limit cold air inlet when the main access door of the facility is utilized.
- Service Section (SES): houses the primary control, air management, thermal control, and nutrient delivery systems of the MTF, as well as the full International Standard Payload Rack (ISPR) plant growth demonstrator [104].
- Future Exploration Greenhouse (FEG): the main plant growth area of the MTF, including multilevel plant growth racks operating in a precisely controlled environment [105].

Using approximately 12.5 m^2, leafy greens (e.g., lettuce, Swiss chard, mustard greens), stem storage crops (e.g., radish, kohlrabi), herbs (e.g., basil, parsley, chives), and fruit crops (e.g., tomatoes, cucumbers, peppers) are cultivated inside the FEG in eight racks using water-cooled LEDs and an aeroponic irrigation system (Figure 2.2). Environmental parameters like temperature, relative humidity, and CO_2 level are automatically maintained by the facility control system.

Since NM III is operated year-round with a summer season (November to February), where 50-60 people work at the station, and a winter season (February to November) with a crew typically of nine people, it is possible to continuously grow plants inside the MTF. The summer season is used to maintain the systems in Antarctica and prepare for the next winter season.

Figure 2.2: View into the EDEN ISS Future Exploration Greenhouse in Antarctica full of plants during the analog mission in 2018. Photo credits: Paul Zabel.

2018 Winter Season Organization and Data Collection

During the 2018 winter season, a tenth individual complemented the wintering crew to operate the MTF. The experiment campaign began with sowing the first plants on 07.02.2018 and continued until the final harvest of all plants inside the greenhouse on 20.11.2018, lasting 286 days. During that season, the EDEN ISS operator conducted a large number of experiments and measurements on the microbial environment [106], horticulture [107], PHM [94, 95], biomass production [38], resource consumption and waste production analysis [108], greenhouse subsystem validation [109], impact of the greenhouse on crew mental health [110], crew time requirements [48], food quality and safety, and remote operation.

The operator measured crew time using a stopwatch and handwritten notebook throughout the whole campaign; however, due to time constraints, not all tasks could be measured, and time was recorded infrequently. Thus, a strong emphasis was placed on plant cultivation tasks for the various crops, while maintenance and repair tasks were not measured – with the exception of subsystem maintenance. Plant cultivation tasks such as sowing, harvesting, and pruning were recorded on a per plant species, per tray basis for 16 different crops, grouped as lettuce, leafy greens, herbs, stem storage crops, and fruit crops. Crew time required to maintain the greenhouse systems was calculated over the whole season, and the time required to perform daily subsystem and plant health checks was also measured. The work time of the EDEN ISS support team at DLR in Bremen, Germany, was not tracked during this season.

2019 Winter Season Organization and Data Collection

There was no additional crew member dedicated to the MTF for the 2019 winter season. Instead, a team of five winterers maintained and operated the MTF, focusing on producing fresh food for the nine-person wintering crew. Nevertheless, this season provided the opportunity to conduct research on crew time demand and remote operations of the greenhouse in the scope of untrained on-site personnel. The EDEN ISS MCC at DLR in Bremen supported the on-site crew via text messages, emails, and phone calls. The teams met weekly over the phone in the first half of the mission and biweekly in the latter mission half to discuss on-site status and the schedule for the subsequent weeks. The team in Bremen also remotely monitored the greenhouse system software, planned tasks for the upcoming weeks, and supported the on-site crew as needed during nominal and emergency situations.

From 29.04.2019 (first organization phone call between on-site operators and the DLR RST) to 01.06.2019, crew time was estimated based on single point measurements and the average crew time recorded throughout the 2019 winter season. The on-site operators began preparations in EDEN ISS on 06.05.2019, and systems in the greenhouse were started on 16.05.2019. From 01.06.2019 until the final harvest on 23.11.2019, the on-site operators tracked daily crew time with a watch or smartphone and recorded times in an Excel file. Due to the lack of a dedicated on-site operator, 2019 crew time values encompassed all daily activities – including the commute to and from NM III – and were not categorized. The tasks included crop cultivation, system maintenance, and repair tasks. No science data, besides harvest yield and crew time, were measured this season. In addition to the on-site crew time values, the specific work time values for the team in Bremen were tracked from 29.04.2019 until 23.11.2019 [2].

2.2.4 Hawaii Space Exploration Analog and Simulation (HI-SEAS)

Hardware and Mission Overview

The HI-SEAS habitat is located on the slopes of the Mauna Loa volcano on the Big Island of Hawaii, at an altitude of 2500 m, far from any human activity, and with minimal animal and plant life (Figure 2.3). From 2013 to 2017, five crews of six individuals selected for their astronaut-like profiles spent four to twelve months within the 110 m^2 habitat, depending on freeze-dried and shelf-stable food and limited water and energy. Crews operated under a 40-minute communications delay with the outside world and could not go outside without a mock spacesuit. The study developed in this chapter includes data collected during three missions, HI-SEAS II, HI-SEAS III, and HI-SEAS IV, which were built upon the same research questions on crew dynamics and cohesion over time when the crew was given full autonomy, especially with regard to their schedules and roles.

The three mission crews grew plants within the HI-SEAS habitat using different set-ups, but lighting timers were consistently the only automated system component. During HI-SEAS II, plants were grown in four trays in the laboratory and in a Biomass Production System for Education (BPSE) (ORBITEC, now Sierra Nevada Corporation), totaling 0.5 m^2 plant growth area. During HI-SEAS III, plants were grown in the laboratory on dedicated shelves, in reused jars in the airlock area, and as decorative plants on desks (not accounted for here). This represented about 1.3 m^2 of growing area. During HI-SEAS IV, the set-up was similar to HI-SEAS III, but there were also two hydroponic systems for a total growth area of about 1.7 m^2. In all three missions, crew members ate the vegetables (mainly leafy greens, cherry tomatoes, and sugar snap peas) and herbs they grew; however, some plant science experiments were conducted.

Figure 2.3: HI-SEAS habitat on the slopes of the Mauna Loa volcano. The white dome (center) is attached to a 6.1 m storage container (right) used as a workshop and storage facility. In the foreground (left), solar panels are the habitat's main power source. Photo credits: Lucie Poulet.

Data Collection Method

Each crew was asked to record time they spent tending plants each day and for each plant-related activity. The categories were: watering, health check, temperature check, sowing, thinning, transplanting, harvesting, pot reorganization, mixing new hydroponics solution, cleaning, increasing light intensity, and taking photos.

One HI-SEAS II crew member was in charge of plant growth and recorded crew time spent on plant care for the whole 120-day mission. Other crew members who tended plants in the BPSE also logged time. The HI-SEAS III crew member responsible for plant growth recorded crew time spent on plant care for 72 days of the eight-month mission. During HI-SEAS IV, four crew members grew plants and agreed to report the crew time on plant care for one month (33 days) of the twelve-month mission.

2.2.5 Mars Desert Research Station (MDRS)

Hardware and Mission Overview

The MDRS habitat is located in the Utah desert and is operated by the Mars Society, enabling scientists to test new technologies, operations, and science experiments in a Mars-like environment, isolated from human activities, among a crew of 6-7 people, for two weeks (Figure 2.4). At the time of data collection in 2014, the greenhouse module attached to the MDRS habitat, called GreenHab, was a horizontal cylindrical structure made of a polycarbonate translucent shell on a metal and wooden framework, and divided into a small zen garden with flowers for crew well-being and a larger part used for vegetable growth and plant experiments over the season, with a growth area of roughly 5 m^2. The prime lighting source was the sun; one supplemental red and blue LED flat circular lamp (called UFO) was available. No operations in the GreenHab were automated in 2014.

Figure 2.4: MDRS GreenHab (left) and crew habitat (right) in February 2014. Photo credits: Lucie Poulet.

Data Collection Method

Three crews recorded time spent working in the GreenHab: crew 135 (03.02.2014 - 14.02.2014), crew 139 (29.03.2014 - 12.04.2014), and crew 140 (13.04.2014 - 27.04.2014). Crew time for plant-tending activities was recorded each day. However, no preset category was given to the crews, and most of the time, crew time was logged for a group of activities rather than per activity (e.g., watering, temperature checks – 5 min). Because of the harsh temperature conditions at MDRS and the temperature gradient between daytime and nighttime, plants had to be covered in the evening and uncovered in the morning, which was often grouped under the activity "temperature checks and watering".

2.2.6 University of North Dakota Inflatable Lunar/Mars Habitat (ILMAH)

Hardware and Mission Overview

The ILMAH is located at the University of North Dakota (UND) in Grand Forks, North Dakota. The three-person crews are isolated from external human contact during 15- to 30-day missions, except for during extravehicular activities (EVA) for safety reasons. At the time of data collection in 2014, the habitat was composed of a 37 m^2 inflatable modular habitat connected to a rover via a tunnel to allow donning and doffing of pressurized EVA suits. There was no greenhouse module, but two shelves accommodated plants and lighting for a total of about 0.5 m^2 growing area. Unlike HI-SEAS and MDRS crews, the ILMAH crew had no autonomy regarding their schedule, which was established by mission control. This also applied to plant care, although the crew was allowed to tend plants more often than scheduled if desired.

Data Collection Method

Crew time for plant-tending activities was collected daily over 30 days for each plant-related activity. The categories were the same as for the HI-SEAS missions.

2.3 Results

2.3.1 Veggie

Table 2.2 summarizes the average time spent on plant care in Veggie. Health monitoring includes plant health and environmental checks, watering, wick opening, and taking photos. Initiation and harvest time also include Maintenance Work Area (MWA) setup. Time for microbiology swabbing for post-flight analysis and for produce sanitization are included within the harvest time. Operations training time includes crew procedure reviews and various video training. Corrective repair includes operations such as adjusting the cabin fan, hardware power resets, and hardware auditing. Scheduled preventive operations include cleaning, post-experiment hardware powering down, stowing, scheduled hardware relocation, and activities associated with the Mass Measurement Device (MMD) and its calibration. Plant data collection activities include science sample handling and crew surveys.

Table 2.2: Average time per task, as categorized in Table 2.1, and standard error values on 13 missions (6 one-month missions, 6 two-month missions, and 1 three-month mission) conducted between July 2014 and December 2019 in the Veggie hardware on International Space Station. Total growth area: 0.13 m^2 (scaled to one Veggie unit); the associated standard error is given after the +/-, classified as in Table 2.1.

Sub-Activity	Operation type	Unit operation	Veggie [min]
Health Monitoring	Undistinguished - incl. watering	(per task)	16.15 +/- 1.35
Cultivation Ops	Starting	Initiation (per task)	122.31 +/- 4.51
	Harvesting	(per task)	69.62 +/- 8.13
	Manual watering	Using a syringe	Incl. in Health Monitoring
Harvest processing	Edible biomass processing	Sanitizing	Incl. in Harvest
Routine Ops	Operations training	(per task)	15.77 +/- 1.62
	Hardware/Facility cleaning	Growth area cleaning	Incl. in Scheduled Preventive
Maintenance	Corrective repair	(per task)	6.54 +/- 2.51
	Scheduled preventive	(per task)	45.77 +/- 3.72
Utilization	Plant data collection	(per task)	13.85 +/- 1.82
Work Prep	Veggie install	(per task)	115.00

2.3.2 EDEN ISS

2018 Season

Table 2.3 lists top-level crew time values from the 2018 EDEN ISS winter season [48]. Zabel *et al.* [48] reported further details regarding these measurements. Most tasks were not performed daily, unless indicated in Table 2.3. Note that "thinning" was performed with scissors to prevent damage to the remaining seedling.

Table 2.3: Average time per task during the 2018 winter season (February to November) in the EDEN ISS Mobile Test Facility at Neumayer Station III, Antarctica. Total growth area: 12.5 m^2. [a] Based on radish crops; [b] Based on cucumber and dwarf tomato crops.

Sub-Activity	Operation Type	Unit Operation	EDEN ISS [min]
Health Monitoring	Environment	Undistinguished (per day)	14.17
	Crops		
Cultivation Ops	Starting	Sowing (per 10 seeds)	1.00
	Adjusting	Thinning (per m^2)	[a] 4.60
		Reorganization (per m^2)	4.58
		Pruning (per m^2)	[b] 43.60 - 49.03
	Harvesting	Lettuce (per m^2)	3.97
		Leafy Greens (per m^2)	23.67
		Herbs (per m^2)	27.32
		Fruit crops (per m^2)	3.77 - 13.52
		Radish (per m^2)	22.05
Routine Ops	Subsystem checks	Incl. in Health Monitoring	
	Nutrient solution mixing/ prep.	(per 10 days/tank)	20.17
	Fresh & waste water management	(per event)	90.00
Work Prep	Greenhouse access	(one-way)	20.00 - 40.00
Conference	Team meeting	(per week per crew member)	60.00 - 120.00

2019 Season

From June through August 2019, the on-site crew spent around 100 h month^{-1} to operate the MTF, with an additional approximate 30 h month^{-1} of remote support (Table 2.4). On-site crew time increased once plants were initiated in the MTF in mid-May, and it decreased after August due to starting preparations for the next summer season in lieu of new plants. Nevertheless, the on-site crew improved in work efficiency and independence in the MTF over time, reflected by the lower remote support time needed from September through November.

In total, MTF operations in 2019 required 549 on-site hours and 146 remote support hours to produce 110 kg fresh edible biomass [2]. As support from the MCC accounted for 21% of total work time, the time required to support plant growth operations remotely should also be considered when planning future space missions. However, we can infer that future crews will be trained on the plant growth module prior to the mission and thus that support from the ground team would be less than the one reported at the MTF. This support time may be converted into training time on the plant growth systems.

Table 2.4: Monthly crew time for the 2019 winter season (April to November) in the EDEN ISS Mobile Test Facility at Neumayer Station III, Antarctica (on-site), and at the Mission Control Center at the German Aerospace Center in Bremen, Germany (remote). [a] *Estimated values based on single point measurements and on the average value of the measured crew time needed for the work in the Mobile Test Facility between 03.06.2019 and 13.10.2019.*

	Crew time on-site [h]	**Work time remote [h]**
April	[a] 0.75	1.50
May	[a] 65.75	26.50
June	98.25	31.00
July	102.00	35.50
August	109.00	27.75
September	76.25	9.50
October	57.50	10.00
November	39.00	4.25
Yearly Total	**548.50**	**146.00**

2.3.3 Analog Missions

Average crew time for the HI-SEAS and MDRS analogs are presented as 3-mission averages, unless otherwise indicated, while ILMAH is presented as a single mission (Table 2.5).

Initiation included transplanting seedlings to larger pots, while light adjusting encompassed raising light fixtures, changing light intensity, or turning lights on/off, depending on the mission. Cleaning events occurred only once during the month when HI-SEAS IV crew reported data, four times over the 30-day ILMAH mission, and only once total over the three two-week MDRS missions. New nutrient solution was mixed once in the three months of data recording during HI-SEAS III, 24 times during the ILMAH mission, and four times total over the three MDRS missions. Thus, depending on facility set-up and size, activity frequency can differ by orders of magnitude.

It should be noted that on the first day of the ILMAH mission, watering took 4 min (average time over the mission is 1.9 min), and temperature checks required 5 min (average time over the mission is 0.3 min). This corresponds to the learning phase the crew had to go through in order to perform plant-related activities with confidence. This time will need to be accounted for in future missions, either by ground training or on-site training upon arrival.

Regarding the nutrient solution mixing, time required for this task varies considerably from one mission to the other, despite the fact that these numbers are normalized per task. This comes from the fact that the systems compared here (hydroponics and soil vs. solely soil-based) and their size (0.5 m^2 vs. 5 m^2) are different, so the requirements for nutrient solution mixing likewise differ. Besides, one instance of nutrient solution mixing at MDRS lasted for 210 min – which is about 11 times higher than the usual average time (18 min) without counting this outlier – contributing to a higher average value of 66.25 min.

Table 2.5 Average time per task for three analog locations collected between January 2014 and August 2016. Total growth area: HI-SEAS: 1.3 m^2; ILMAH: 0.5 m^2; MDRS: 5 m^2. The HI-SEAS and MDRS columns are the average between three missions, unless otherwise stated: [a] Average from one mission; [b] Average from two missions; [c] This includes daily check operations and plant watering. n/a = not applicable; n.m. = not measured.

Sub-Activity	Operation Type	Unit Operation	HI-SEAS [min]	ILMAH [min]	MDRS [min]
Health Monitoring	Environment	Temperature, relative humidity, CO_2	[a] 2.13	0.26	[c] 29.71
		(per task)			
	Crops	Disease, pathogens (per task)	3.95	1.30	
Cultivation Ops	Starting	Sowing (per task)	[b] 20.19	12.50	[b] 70.00
		Initiation (per task)	[b] 34.13	15.00	[b] 19.00
	Adjusting	Thinning (per task)	[b] 5.10	4.00	n/a
		Reorganization (per task)	[b] 12.15	2.10	[a] 10.00
	Harvesting	(per task)	19.01	3.50	[a] 30.00
	Manual watering	(per task)	5.64	1.92	n.m.
Routine Ops	Operations training	(per task)	[a] 2.75	n.m.	n.m.
	Routine cultivation parameter adjustments	Light adjusting (per task)	10.71	0.01	n/a
	Nutrient solution	Mixing (per task)	[b] 31.07	1.25	66.25
	Hardware/Facility cleaning	Cleaning of cultivation area (per task)	[b] 41.00	3.25	[a] 40.00
Maintenance	Corrective repair	Equipment repair (per task)	n.m.	n.m.	[a] 10.00
		Insect traps (per task)	n/a	n/a	[a] 20.00
Utilization	Plant data collection	Photos (per task)	3.25	2.17	[a] 6.67
		Other (per task)	[a] 45.00	1.67	

2.3.4 Crew Time Predictions

Scenario Considerations

The results presented in Subsections 2.3.1, 2.3.2, and 2.3.3 provide an estimate of crew time required for routine, maintenance, and repair operations in a greenhouse module in long-term analog facilities and in small-size plant growth hardware on ISS. In this subsection, we use these data to predict changes in crew time needed to operate plant growth systems in future human exploration missions. We distinguish three phases, where main differences are summarized in Table 2.6:

- Future space station
- Interplanetary travel (e.g., transit to Mars)
- Planetary surface operations (Moon or Mars)

In current plans and scenarios, plants will supplement the astronauts' diet during interplanetary travel to Mars, but for the first missions in a future space station and on the Moon (in the 21st century), science and options for plant growth may be limited.

Table 2.6: Differences between mission phases.

	Future Space station	**Interplanetary travel**	**Planetary surface**
Gravity	Microgravity	Microgravity	Reduced gravity
Communications delay	About a second	Several minutes	Up to 22 min (one-way)
Communications blackout	Yes	Yes	Yes
Crew autonomy	Similar to International Space Station	Increased	Increased
Volume	Similar to or smaller than International Space Station	Similar to International Space Station	Larger than International Space Station
Mission duration	Several months	Several months	Weeks to years

Factors and Assumptions Governing Space Greenhouse Crew Time Requirements

These three generic scenarios have implications in terms of crew time available for plant care, which reflect on the type(s) of crops chosen, as well as on choices for watering systems, health and environmental monitoring systems, sowing and harvesting methods, operations training, management of cleaning operations and consumables, maintenance, dormancy, new hardware, and number of operators. In the following, we detail different factors, which influence crew time needed in a space greenhouse, and assumptions, which will be needed to predict what amount of crew time is required for a given task in a given scenario.

Available crew time for plant operations: Overall available crew time may be larger during interplanetary transit missions than on ISS, since other operations currently accounting for much crew time on ISS may not occur as frequently or at all, such as EVAs, regular docking and undocking of vehicles, and regular loading and unloading of cargo ships; communications for public relations, briefings, and tag-ups may also require less time, as they would not happen in real-time. Therefore, interplanetary travel missions to Mars may include one or more plant growth systems, with a larger size than current ISS plant growth units, for supplemental food production to provide necessary vitamins and nutrients [97]. Having a significant amount of plants involving human interaction in a Mars transit mission will keep astronauts busy doing meaningful work on a long journey, which is important to fight boredom and may provide them with some psychological support [111, 112].

However, available crew time for science activities may be the time left after general routine and maintenance tasks (pertaining to spacecraft and crew members) are completed. Here, we focus on crew time needed to operate a plant growth system that would be dedicated to growing food, not focused on science experiments on plants. We still envision that small science experiments such as testing different growth approaches, mood questionnaires, or microbial swabbing could be included.

Current scenarios for future space stations are shorter duration stays than those on ISS or interplanetary travel. Hence, the assumptions made for interplanetary missions regarding available crew time for plant care may not be as relevant in this scenario. Greenhouse modules on the Moon or Mars are expected to be integrated into a regenerative life-support system [113] and larger than plant growth hardware in a transit mission or on ISS.

Type of crops: Measurements of the 2018 experiment phase inside the EDEN ISS greenhouse were performed on a per plant species basis. The results show a large variation of required crew time across the various plant species. Crops that are cultivated in batches with a single harvest (e.g., lettuce) have much lower crew time demands compared to fruiting crops (e.g., tomato), which need regular treatments like pruning of side shoots and re-positioning [48].

The type of crops envisioned for an interplanetary transit mission or a future space station – to a lesser extent – are leafy greens and microgreens [114, 115], as a supplement to the crew's diet, since they are fast and easy-to-grow crops. These types of crops have a high harvest index and require limited tools for harvesting (a pair of scissors). Certain varieties of leafy greens also allow for cut-and-come-again repetitive harvesting, which reduces system initiation time.

On planetary surfaces, the same types of crops (fast-growing crops with a short shelf life) can be grown at first, with the addition of fruiting and root salad crops, as well as herbs, for short-duration missions. Then, for longer-duration missions for which an increasing self-sufficiency from Earth is desired, high-value fruiting crops (e.g., tomato, pepper, strawberry), staple carbohydrate crops (e.g., potato, wheat, sweet potato) and protein/fat-rich crops (e.g., soybean, peanut) crops could be added to the diet [116, 117]. These crops have longer growth cycles and may require specific cultivation and harvest techniques, which require more tools and equipment, as well as cooking and processing equipment for consumption. For example, crew members in BIOS-3 spent on average 8 min day^{-1} m^{-2} grinding wheat [47], which corresponds to 8 min day^{-1} to process approximately 100 g wheat flour [102]. However, these types of crops can also be optimized photosynthetically with high light, thereby contributing more to O_2 regeneration, CO_2 removal, and the overall diet [118]. Plant propagation stock through seed or clonal materials is also something to consider for long-duration missions.

Watering: Current watering options on the ISS include the early proof of concept approaches used in Veggie (human-operated syringe) and APH (automated porous tubes) [99]. A number of other automated substrate-free or reduced substrate watering systems are being considered and tested for microgravity (i.e., for future space station and interplanetary missions). In the few instances when crew time needed for watering crops in Veggie was recorded independently from other daily tasks, it averaged 10 min day^{-1} for six plants. For larger scale systems that would be installed in an interplanetary ship, crew time needed for watering would likely be lower. Techniques involving improved, passive capillary watering and full automation could reduce crew time and would be more desirable for microgravity phases of exploration missions.

On planetary surfaces, watering and nutrient solution mixing could be performed with fully automated hydroponics or aeroponics systems, which would considerably reduce crew time dedicated to watering and system mass by allowing water and nutrient recycling with no solid media waste [119]. However, it may require more crew time for maintenance and repair since more subsystems are likely to break in such a system compared to manual watering. For instance, the EDEN ISS facility aeroponics system was subject to several maintenance and repair activities due to high-pressure pump failures.

Health and environmental checks: For all mission types, autonomous or remote environmental monitoring and control loops for temperature, relative humidity, CO_2, and light (this is already done, for example, in the APH on the ISS) would reduce crew time dedicated to daily plant and environmental checks. Systems coupling sensing techniques such as multispectral and hyperspectral imaging with stress and disease identification algorithms could allow early detection of plant stress and remove this from the crew duties [95]. If the crops are grown in an atmospherically closed environment, monitoring their photosynthetic CO_2 uptake during the day, respiratory CO_2 production during the night, and transpiration can all provide important measures on overall crop performance and stress [120, 121]. In all three scenarios, health and environmental checks can be fully automated and, for example, performed by an artificial intelligence (AI) assistant.

Sowing and harvesting: We assume that for future missions in microgravity (i.e., future space station and interplanetary missions), initiation will consist of sheets with pre-sown seeds needed to be inserted in the system, as well as turning on watering and health and environmental controls. Using the cut-and-come-again method, when suitable, will also reduce the frequency of initiation activities. System initiation in Veggie on the ISS currently involves watering, health and environmental checks, and MWA setup.

For microgravity phases with small-scale systems, thinning and harvesting should be executed by the crew to maintain human interactions with plants. Currently, Veggie harvests last about 70 min on average for six plants since harvesting events also include scientific data collection such as photos, microbiological swabbing, sample weighing, produce sanitization, and collecting and freezing samples for return to Earth. However, a future plant system strictly intended for food production would significantly reduce estimated harvest time required and approach full automation. We can also infer that for future missions, produce sanitization will be semi-automated, and astronauts will only have to leave produce in a system that will perform the cleaning.

In both microgravity and planetary surface systems, most postharvest processing operations should be automated. On planetary surfaces, harvesting and sowing will likely be automated, but this will result in more crew time required for maintenance and repair. Schwartzkopf [102], with technologies of the early 1990s, estimated that while automating harvest, sowing, and nutrient solution maintenance would eliminate crew time associated with these activities, it would generate a 10% increase in crew time dedicated to maintenance [102]. Trade-off studies will be necessary once technologies have been chosen to weigh in crew time spared on harvesting against crew time added to maintenance.

Operations training: The current assumptions for long-duration missions (i.e., interplanetary and planetary missions) are that crew members will be trained on plant growth systems prior to leaving Earth and that crew procedures (e.g., harvesting) will not need to be reviewed as frequently since the crew would use the plant growth system on a quasi-daily basis. This would eliminate the learning curve phase for these particular tasks.

For future missions that will be shorter in duration and with possible intermittent occupation (e.g., a future space station), these assumptions may not be realistic anymore. The existing on-board training (e.g., for Veggie) – videos that the crew watches before starting an experiment – could be coupled to a VR environment. In addition, an AR system with procedures and tutorials could be used aboard the station as needed and during new operations. This could allow astronauts to stay current on skills and rehearse operations, enabling faster training, and limiting human error in performing certain tasks – which translates into less crew time needed to fix them [86].

Cleaning and consumables management: Since cleaning is time-consuming and among the least liked tasks by the crew, according to feedback provided by astronauts and analog astronauts, this should be automated as much as possible, both for microgravity (i.e., future space station and interplanetary missions) and surface systems.

In both microgravity and planetary surface systems, consumables management could be entirely managed by a virtual assistant or a simple control system that alerts crew members when consumable stocks are low.

Maintenance: Crew time for maintenance operations cannot be linearly computed on a m^2 basis since it encompasses fixed portions, which are independent from the system's growth area. Maintenance operations will also depend on the final system design, which will likely vary significantly from current ones. However, with increased automation, it is reasonable to assume that a large portion of crew time dedicated to maintenance will focus on automated systems. The increased time needed for maintenance will subsequently increase the risk of human error, so crew time dedicated to manage human errors should also be included [96].

For instance, scheduled preventive operations as computed for Veggie include, among others, cleaning, powering down, stowing, and hardware relocation. Stowing and hardware relocation are likely to be less frequent on an interplanetary or surface mission because plant systems for long-duration missions would be used more regularly and, thus, would tend to have a more fixed location. However, these operations may still be frequent on a future space station.

To further reduce crew time needed for repair and maintenance, AI support combined with an AR assistant could be used to track maintenance schedules and help with repairs. For example, the astronauts could wear AR glasses while conducting activities and have assistance showing the schematics of the system being repaired or what pieces to access. From the increased level of automation in long-duration plant growth systems (for watering, monitoring, sowing, harvesting, and cleaning) coupled with higher level of real-time assistance for repair and maintenance, we can infer two things:

- In short-duration missions in future space stations, repair and maintenance of plant growth systems would require less crew time than currently on ISS, thanks to coupled AI-AR assistants.
- In long-duration missions (interplanetary travel and surface), crew time needed for repair and maintenance would likely be larger than currently on ISS, because maintenance and repair activities would be more frequent due to more complex systems, inherently more prone to failures.

Dormancy: Dormancy phases between crewed periods, such as in a part-time inhabited space station like that envisioned for Gateway, should not be overlooked. This would increase maintenance time for powering up the system. Indeed, during the 2019 experiment phase, there was increased fungal and bacterial growth upon restart of the EDEN ISS facility after several months of inactivity, resulting in delays because additional time was needed to deep clean all systems. It may be useful to determine what systems should be running during hibernation in order to save time, labor, and resources upon restarting. However, if an AI assistant is built into the plant system, end-of-dormancy procedures could be completed prior to crew arrival.

New hardware: When new hardware needs to be installed prior to starting operations in a plant growth facility, it increases crew time needed to grow food in space. Installing the second Veggie unit on the ISS took 115 min, without including deactivation time after initial testing was completed. The relocation of a Veggie unit takes about 60 min.

Number of operators: Multiple untrained people learn slower than one single untrained person. In addition, the feeling of responsibility for the system and the plants is higher when fewer people are involved. This suggests it might be best to have one trained person – a horticultural mission specialist – and one backup for future space plant facilities. Schwartzkopf [102] suggested that each crew member could spend some time supporting the plant growth system during their leisure time to reduce working crew time needed to operate the system [102], arguing that crew members seemed to like spending time tending plants in the BIOS experiments. However, a leisure activity tends to switch to the work category as soon as a mandatory aspect is added. Moreover, there are individual variations in affinity for working with plants, and while some crew members might perceive it as leisure time, it may become a burden for others. This would accentuate the challenge of having multiple people working sometimes on the plant system versus having trained crew members working on it regularly.

2.4 Discussion

2.4.1 Recording Inaccuracies

We are aware that data collected in the analog facilities may be only a partial representation to a certain extent. First, because crew members of these missions were already asked to report a large number of other data, their performance in terms of crew time recording may have decreased over time. This is why data reported here on analog facilities are rarely on the whole duration of the mission, but rather on a small portion. Additionally, the crew sometimes forgot to record crew time and did it later in the day or in the week, so the recorded crew time may incorporate inaccuracies. Moreover, crew members were often multitasking, and it may have been challenging to distinguish crew time dedicated to a single task. The way crew members recorded crew time also varied from one individual to another with respect to skills, motivation for the task or individual tempo for task execution, and accuracy. Therefore, for future crew time measurements, it may be wise to use an external measurement device or another person – keeping in mind that the system used should be user-friendly and reliable.

Although the data presented here includes a "research" sub-activity (Utilization) for each facility, some research tasks were fully embedded into other operational tasks and were indistinguishable from food production activities. Therefore, the data presented here probably inflated crew time with a confounded "research" component. For example, in the case of Veggie, we estimate that at least 50% of the harvesting crew time could be eliminated with a non-research food production system; in the HI-SEAS II mission, harvesting crew time could have been reduced by at least 70% if the only purpose of the plant systems had been food production.

2.4.2 Crew Time to Decide on Greenhouse Architecture

As highlighted by Russell *et al.* [45], crew time can be a defining criterion when selecting technologies for a space mission [45]. Indeed, if crew time required to operate a given technology is higher than the available crew time after subtracting time needed for personal and habitat maintenance and mission operations, this technology is probably not viable (Figure 2.5). In designing future greenhouse modules for planetary surfaces and interplanetary travel and choosing technologies that will enable adequate crop production, crew time should be among the decisive criteria. This process could also be used for plant species selection.

As discussed in Subsection 2.3.4, some systems require less routine crew time because they are automated, but because they are more complex, they have higher failure rates, generating more crew time needed for repairs. There is thus a direct trade-off to be made between systems that require less routine crew time but more corrective maintenance time and systems that are more crew time intensive but break less often. This crew time consideration will have a direct impact on designing future space greenhouse modules.

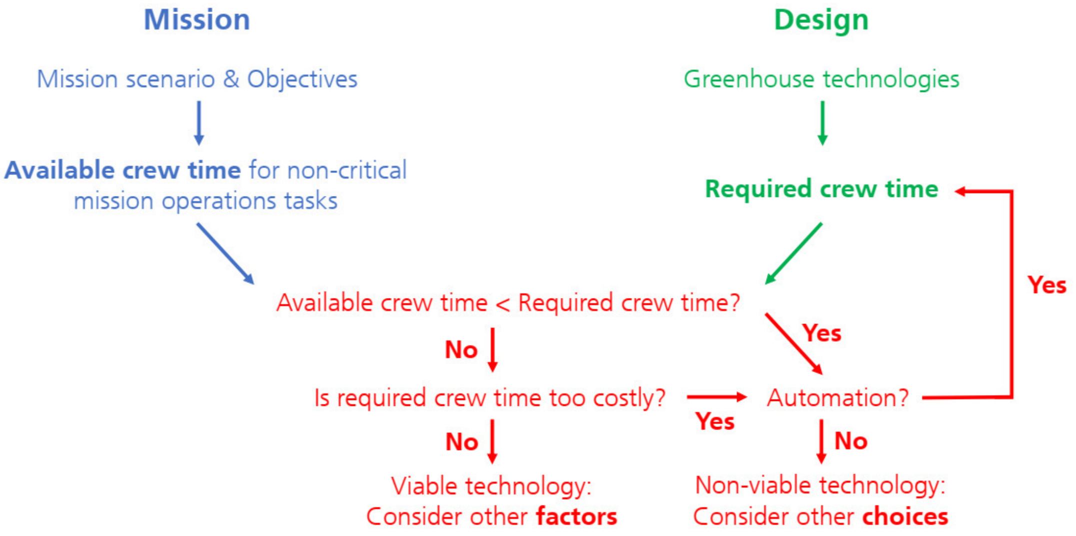

Figure 2.5: Decision tree to use crew time in technology selection. Reproduced and modified from Russell et al. [45].

2.4.3 Importance of Developing a Methodology

As detailed in Subsection 2.4.1, reporting crew time while operating a plant growth system can lead to difficulties in reporting. Therefore, limited data have been collected in operational environments over the years. When data were collected, tasks were often pooled together; when data were categorized, this was done differently in each facility. However, as detailed in Subsection 2.4.2, crew time ought to be a decisive criterion in greenhouse module design. To efficiently plan for crew time needed for plant care in distant space destinations, we need to be more specific than just reporting daily averages, and we need to identify time-consuming, recurring, or exceptional tasks. To tackle this challenge of crew time reporting and lack of data, we suggest following a standardized methodology, which consists of:

- Identifying the different tasks needed to operate the greenhouse module in relation to Table 2.1
- Defining a representative time period for data collection
- Accurately reporting crew time for individual tasks – and their occurrence
- Using collected data to improve greenhouse modules and plant growth systems designs

Ultimately, for accurate mission planning, it would be beneficial to conduct a series of experiments dedicated to crew time recording in an Earth-based facility recreating close-to-real conditions in space greenhouse modules. This would enable to fine-tune crew time measurements and estimates in analog facilities and on the ISS.

2.5 Conclusion

Crew time data for different plant growth systems on ISS (Veggie) and on Earth (different Mars analogs and the EDEN ISS research facility) were reported. This led to the identification of gaps and lack of uniformity in data reporting. We provide here a methodology for categorizing and reporting crew time which will enable standardization.

Crew time needed to operate plant growth systems can be reduced with adequate choices of crops, automation, AI and virtual assistants, and sufficient crew training. In microgravity phases, a plant growth system that is intended to supplement the crew's diet could preferably include leafy greens and microgreens. This system would be equipped with automated watering, lighting, health and environmental checks, an AI managing maintenance schedules, and a virtual assistant for repair activities. Crew time ought to be a decisive factor for plant species choice and plant growth system architecture and operations.

Chapter 3

Detailed Crew Time and Workload Investigations

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Life Sciences in Space Research

Crew time and workload in the EDEN ISS greenhouse in Antarctica

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Chapter 3 builds upon Chapter 2 to investigate research questions **RQ1** and **RQ2** of this thesis further. In particular, the crew time database from Chapter 2 is extended and further elaborated with data from the crew time investigations conducted during the space analog EDEN ISS missions.

Analysis and comparison of crew time required by the greenhouse OOT and RST at the MCC were performed (**C1**). The data indicated that the RST required a significant portion of the total crew time (sum of RST and OOT crew time) during the space analog mission. Furthermore, data on the evolution of weekly and monthly crew time requirements throughout a season were added to the research field (**C1**). Similar to Chapter 2, a standardized methodology for measuring the crew time of the RSTs in the MCC was developed, allowing for comprehensive assessments and comparability of crew time requirements (**C4**).

To complement the crew time values and better understand future space greenhouse operations, the workload of the EDEN ISS greenhouse operator teams (remote and on-site) was measured (**C1**).

The data presented in this chapter supports the need to optimize crew time allocation for future space greenhouse operations and highlights the importance of minimizing perceived workload. Research is presented on which NASA TLX dimensions most impact overall workload. These findings demonstrate the importance of the collected crew time and workload data as a basis for the planning, design, and operational processes of space greenhouses on the Moon and Mars to ensure reliable and efficient operations (**C1**).

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3.1 Introduction

During long-term space missions, it is necessary to address the serious problem of a lack of certain nutrients and vitamins [97, 122, 123]. The cultivation of higher plants during planetary surface missions will help to produce oxygen, reduce carbon dioxide, manage waste products, and recycle water [10]. Moreover, plants have a positive impact on mental health and human performance by reducing depression and anxiety, and increasing attentional capacity and self-esteem, among other benefits [11, 111, 124]. The consumption of fresh vegetables is also beneficial to the physical and psychological health of the crew [125–127].

Concepts for planetary surface habitats on the Moon and Mars include greenhouses as part of an independent food production system for the astronauts. Examples of ground-based testbeds include NASA's Biomass Production Chamber [128], the Lunar Greenhouse [129], the SPFGC [33], the Arthur Clarke Mars Greenhouse in the Canadian high Arctic [32], the series of BIOS projects [30], or the Lunar Palace [29].

Within the EDEN ISS project, a greenhouse facility was built in Antarctica to test key technologies for use in future planetary surface greenhouses under extreme environmental and logistical conditions [34, 35, 130, 131]. The greenhouse, called MTF, was installed near the Neumayer III Antarctic Research Station (NM III, 70°40'S, 8°16'W), which is operated by the Alfred-Wegener-Institute for Polar and Marine Research (AWI) [36, 37]. The greenhouse is operated by at least one on-site operator, who is part of the NM III wintering crew, with support from the MCC at the DLR Institute of Space Systems in Bremen (Germany).

Due to its similarities with the Moon and Mars, the Antarctic environment has been selected over other sites on Earth. It serves as an important space analog test site due to its environmentally harsh conditions and low biodiversity. In addition, the crew of the NM III Antarctic research station has a size of nine people during the winter season and is highly isolated and dependent on technology, which is similar to aspects of future space missions on planetary surfaces. [18, 131] The crew also has to face several limitations, including the lack of resupply during the winter season and limited communication via a permanent satellite link with AWI in Bremerhaven (Germany), which has a low data bandwidth of approximately 1-2 Mbit s^{-1} for the whole research station [132]. Another similarity between the NM III wintering crew and future astronauts is the importance of crew time utilization. A significant fraction of the wintering crew's crew time is required for scientific activities, so the crew time effort to maintain NM III and the EDEN ISS greenhouse should be minimized as much as possible.

The first contribution of this chapter is to provide detailed crew time estimates for the 2019 experiment phase (April to November). The objective is to add relevant crew time data associated with the corresponding edible biomass production to the field of research while providing insights into the crew time demand of the OOT for the EDEN ISS space analog greenhouse and the crew time[a] demand of the RST in the MCC. In addition, the development of crew time of the two teams and the crew time distribution between the two teams over the course of the 2019 experiment phase is analyzed. Derived from the measured crew time values for the RST 2019, a methodology is presented to categorize the crew time needed for remote support. The second contribution is to provide an assessment of workload regarding the operational activities related to a space analog greenhouse. To achieve this, the workload of the OOTs during the experiment phases in winter seasons of 2019 and 2020, the SMT during the 2019/2020 summer season, and the RSTs during the experiment phases in 2019 and 2020 is assessed using the NASA TLX questionnaire. Based on the results of the NASA TLX, possible solutions for workload optimizations are proposed. The final key contribution is the examination of the crew time impact and the workload investigation results for the planning and operation processes of future planetary surface missions with greenhouses incorporated into the habitat infrastructure.

3.2 Related Work

3.2.1 Crew Time and Workload in Space Missions

Efficient use of crew time is key for the scientific success of space missions. Crew time is a limited and expensive resource on a space mission [40, 41]. The current pricing policy rate to support commercial/marketing activities on the ISS is 130,000 $ h^{-1} [42]. For planetary surface missions, these costs will increase further. Consequently, crew time has to be minimized as much as possible [32, 47].

Furthermore, Coleshill *et al.* [44] reported that 2.5 full-time crew members were needed for the assembly and housekeeping tasks onboard the ISS. During that time, the crew onboard the ISS consisted of only three people. Due to this, only 20 crew member-hours (CM-h) per week were available for scientific tasks without considering unplanned activities [40]. According to Russell *et al.* [45], crew time needed for scheduled and unscheduled maintenance of the ECLSS onboard the ISS was 13 to 15 times higher than the crew time value of 50.0 CM-h $year^{-1}$ (1.0 CM-h $week^{-1}$)

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[a] The term crew time is normally applied to astronaut crews and not to the number of hours worked by remote support teams (e.g., mission control teams on Earth). Nevertheless, the term crew time is also used in this thesis for the working time of the remote support teams to facilitate the crew time comparisons between the teams involved in the operation processes of the EDEN ISS facility.

estimated during the design process. In addition, on Skylab, 0.75 CM-h day^{-1} per crew member were considered for housekeeping tasks, but the actual average value was 1.1 CM-h day^{-1} per crew member. Also, on Mir crew time for unscheduled maintenance tasks was higher than planned, while other activities, such as sleep, were reduced to be able to accomplish additional maintenance tasks [45]. As a consequence, this could have a negative effect on the crew's psychological well-being [46] and can consequently endanger the outcome of a space mission. As seen, actual required crew time generally exceeded the planned crew time in past space missions due to higher amounts of scheduled maintenance and unexpected tasks, so more knowledge and effort are required to define and assess crew time needs for future space missions [45].

Aside from crew time, perceived workload is also of interest to mission planning. Negatively perceived or evaluated tasks could adversely affect crew well-being and should be prioritized for automation if possible. Unfortunately, published literature lacks such baseline crew time data and workload measurements, especially for the operation time of planetary surface greenhouses, which is heavily needed for planning.

International Space Station

There are publications regarding crew time investigations for the ISS, but none are related to plant cultivation activities. Russell *et al.* [45], Mattfeld *et al.* [46], and Anderson *et al.* [133], for example, reported crew time values for a typical workday of the crew onboard the ISS. The astronauts on ISS work approximately 8.5 CM-h weekday^{-1} and 0.3 CM-h day^{-1} on weekends, with eight days of vacation per crew member per year [133]. One week consists of five weekdays and two days of weekend.

There is some overlap in the categorization of crew time in the literature. Nevertheless, as there is often only partial overlap, it is difficult to compare the crew time values for specific tasks. In Stromgren *et al.* [41], a methodology is presented for crew time categorization divided into work and non-work activities for the ISS, which was also used in Mattfeld *et al.* [46]. Stromgren *et al.* [41] subdivide these categories into sub-categories, activities, sub-activities, and operation types. This simplified methodology of Stromgren *et al.* [41] can help to compare the values of various publications in the future. Furthermore, some crew time values for specific ISS tasks are shown and adjusted with respect to future Gateway missions.

Mattfeld *et al.* [46] discuss potential utilization time for science activities and a crew time model for a crewed Mars mission. However, as mentioned previously, there are no tasks presented related to planetary surface greenhouses. For example, the time needed for meals (12.25 CM-h week^{-1}) and preparation (2 CM-h week^{-1}) accounts for 14.25 CM-h week^{-1} for a Mars surface mission. These numbers solely consider the use of the MRE without the cultivation of plants in a greenhouse, which would add additional crew time for such missions and would result in the need to reduce crew time for other tasks presented in Mattfeld *et al.* [46] such as public relations or pre/post-sleep.

Planetary Surface Analog Greenhouses on Earth

Nevertheless, there is also literature with crew time values for work in planetary surface analog greenhouses on Earth. As reported by Schwartzkopf [102] and Eckart [47] in the Russian BIOS-3 experiments, higher plants were cultivated in two phytotrons, each with 17 m^2 of growth area for wheat cultivation and 3.5 m^2 for miscellaneous vegetable cultivation. During the experiment period of six months (December 1972 to June 1973), three people were living and working in the BIOS-3 life-support testbed. Crew time was measured in CM-h day^{-1} m^{-2} for plant-related tasks like planting, harvesting, wheat grinding, observation, preventive maintenance, and nutrient solution maintenance [47, 102].

Another example of a planetary surface analog greenhouse is the Mars-Lunar Greenhouse [129]. The daily average of 36 min of labor inside the greenhouse was observed during the nine months long Phase 1 of NASA's Ralph Steckler grant program between 2009 and 2010, where lettuce, tomato, and sweet potato were simultaneously produced as a multi-cropping production system within the single environment of the Mars-Lunar Greenhouse [129].

Patterson *et al.* [33] reported about the winter season from January to October 2006 at the Amundsen-Scott South Pole Station, where various crops such as lettuces, herbs, tomatoes, peppers, cucumbers, cantaloupe, and edible flowers were cultivated on a growth area of 22.77 m^2 in the SPFGC. The crew time for the various tasks of the SPFGC operator was tracked and divided into three categories: (1) daily, such as checking the computer and data acquisition system or watering seedlings, accounted for 1.6 CM-h day^{-1}, (2) weekly, such as harvesting or seeding, for 1.5 CM-h day^{-1}, and (3) monthly, such as filling and mixing concentrated stock solutions, for 0.2 CM-h day^{-1}. A total of 23 CM-h week^{-1} of crew time was needed by the operator to maintain the SPFGC [33]. However, not all crew time required to operate the SPFGC was considered in the measurements. For some tasks related to the greenhouse operations, volunteers were organized to support the greenhouse operator. The crew time of the volunteers was not included in the measurements [134]. Also, the crew time for maintenance and repair activities for the primary hardware systems was not included [33].

Zabel *et al.* [48] investigated the crew time for different crop species as well as complete workdays for the 2018 experiment phase during a period of 286 days in the course of DLR's EDEN ISS project. According to the results of the study by Zabel *et al.* [48], the various types of tasks conducted in a planetary surface greenhouse can be divided into four categories: crop cultivation, maintenance, repair, and science. The crew time required to maintain the system is higher than the crew time required for the plant care. Another finding of Zabel *et al.* [48] was the fact that each crop species requires a different number of tasks to be performed and, consequently, requires varying amounts of crew time during cultivation, so it is important to choose the most suitable crop for a space mission. This statement is also supported by Schwartzkopf [102]. In light of this, Zabel *et al.* [48] also emphasized that plants with high mass yield and low occupation time requirements, such as cucumbers, some leafy greens, and lettuces, should be grown in a space greenhouse. On the other hand, herbs, dwarf tomatoes, and radishes had the smallest ratios between yield and needed crew time. Indeed, even though radish plants grow very fast, their crew time demand for harvest is higher because they are multiple single plants and their tuber needs to be separated from the leaves. Additionally, the crew time for greenhouse maintenance, which is strongly dependent on the architecture of systems and components, should be as small as possible to enable more scientific work during a space mission [48].

There are also space analog test sites whose primary scientific focus is not plant cultivation but which include plant growth facilities on their premises, such as the HI-SEAS or the MDRS missions.

From March to June 2014, a 120-day simulation of a mission on Mars was conducted at the HI-SEAS analog test site. [23] During that period, lettuces (2x27 days) and radishes (2x20 days) were cultivated on plant trays under LED lighting in a semi-controlled environment inside the habitat. Besides the lighting investigations, crew time for plant cultivation operations such as watering, temperature checking, sowing, or harvesting were measured and reported per task and as total values. [23]

Since 2002, as described by Poulet and Doule [20], a greenhouse module with a growth area of 5 m^2, called GreenHab, has been attached to MDRS via a simulated pressurized corridor. Crew time needed for cultivation of the plants was recorded for crew 135 (03.02.2014 - 14.02.2014), crew 139 (29.03.2014 - 12.04.2014), and crew 140 (13.04.2014 - 27.04.2014). The greenhouse officer had to take care of all tasks related to the GreenHab since no tasks were automated in the greenhouse. The crew time readings in average minutes per day are divided by tasks, such as watering, covering/uncovering plants, or harvesting, and finally clustered into daily operations, exceptional operations, and maintenance [20].

The previously mentioned studies regarding crew time have shown that there is little research on crew time, especially with a focus on planetary surface greenhouses. Furthermore, we are not aware of any studies regarding crew time of the RSTs of planetary surface greenhouses or workload measurements inside the planetary surface greenhouse or of the RST. In contrast to the related work, this chapter provides a more fine-grained analysis of the crew time and workload for the greenhouse operators on-site and the corresponding RST.

3.2.2 EDEN ISS

The EDEN ISS MTF is deployed at a distance of approximately 400 m from NM III on top of an external platform. The NM III supplies power, water, data, and waste processing for the MTF, similar to the relationship between future greenhouses and habitats. The MTF consists of two 20-foot-long high cube containers: The FEG container and the SES container, which comprises the SES and the CPO, as can be seen in Figure 3.1. [104, 105, 131]

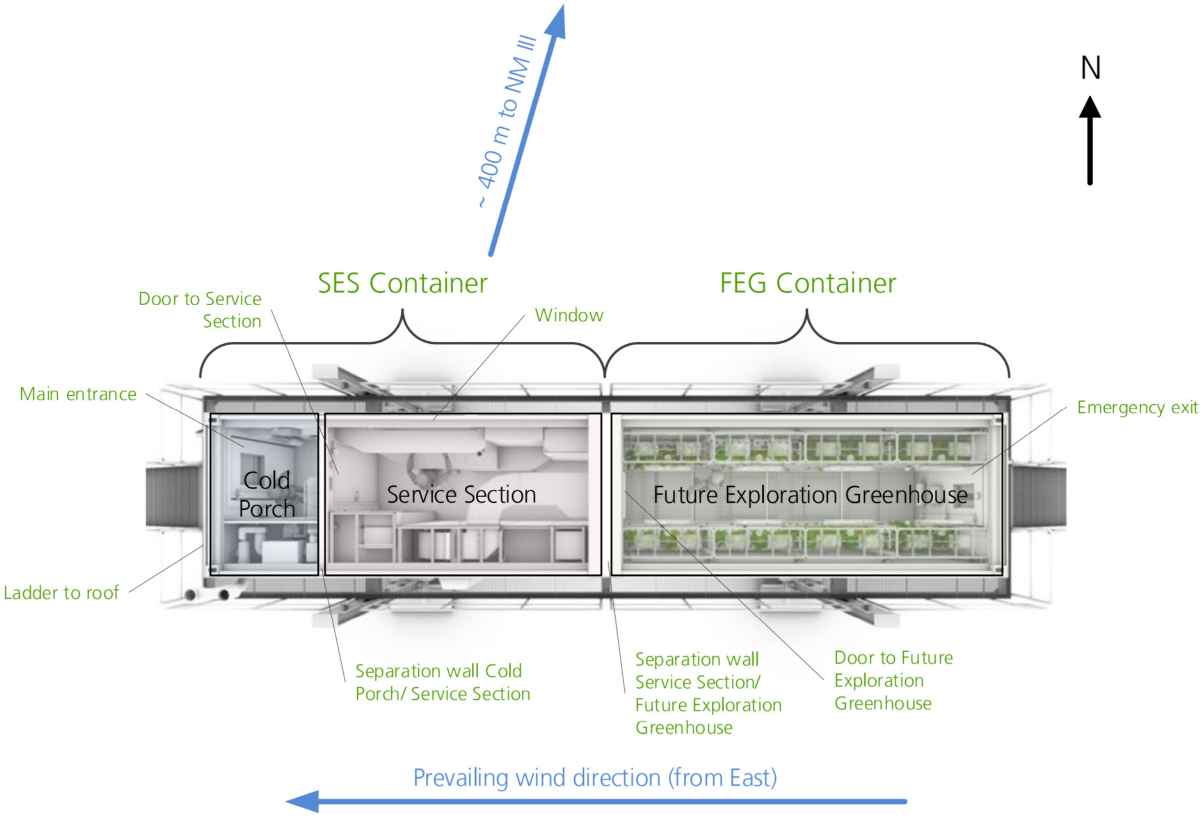


Figure 3.1: Overview of the EDEN ISS Mobile Test Facility main elements. SES = Service Section; FEG = Future Exploration Greenhouse; NM III = Neumayer Station III. Reproduced and modified from Zabel et al. [130].

The fresh vegetables produced in the MTF on a growth area of 12.5 m² are consumed by the wintering crew of the NM III. During the 2019 winter season, approximately 110 kg of edible fresh biomass was produced inside the MTF. In Table 3.1, the monthly edible fresh biomass output is depicted as a sum for all cultivated plants. Table 3.2 shows all crops cultivated in the MTF during the 2019 experiment phase.

Table 3.1: Monthly fresh edible biomass harvest for all crops grown in the Mobile Test Facility during the 2019 experiment phase, as reported by Vrakking et al. [35]. The values were updated due to a processing error in Vrakking et al. [35].

Month	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**Total**
Edible fresh weight per month [kg]	0	0	4.97	14.39	29.01	26.67	23.99	11.02	**110.04**

Table 3.2: List of all crops grown in the Mobile Test Facility during the 2019 experiment phase.

Plant Group	**Type**	**Cultivar**
Lettuces	Frisée	*Expertise RZ*
	Romaine	*Dragoon, Outredgeous*
	Green leaf	*Waldmann's green*
	Batavia	*Othilie RZ*
	Oakleaf	*Cook RZ*
Leafy greens	Asian green	*Tatsoi, Shungiku*
	Mustard green	*Red Giant, Amara, Frizzy Lizzy*
	Pak choi	*Rosie, Pak Choi (extra dwarf)*
	Kale	*Red Russian, Nero Di Toscano*
	Swiss chard	*Bright Lights*
	Wasabi	-
	Rucola	-
Herbs	Basil, oregano, peppermint, lemon balm, water cress	-
Fruit-bearing crops	Tomato	*Cherry, Pick-a-Tom Orange, Hoffmanns Rentita, Rotkäppchen*
	Cucumber	*Picowell RZ*
	Pepper	*Cupid, 1601-M*
Tuber crops	Radish	*Raxe*
	Kohlrabi	*Superschmelz, Korist*

3.3 Crew Time and Workload Recordings within EDEN ISS

3.3.1 Hardware and Mission Overview

The NM III is operated year-round. A season in Antarctica is divided into a summer season (from November to February) and a winter season (from February to November). During the summer season, 50-60 people [131] work at the station to maintain the technical systems, carry out scientific work, and prepare the next winter season. The previous wintering crew trains the new crew and at the end of the summer season, the work is handed over to the new wintering crew. The members of the wintering crew are chosen every year by AWI using a multi-stage selection process.

During the 2018 winter season, a tenth wintering crew member from DLR was at the station to operate the EDEN ISS greenhouse full time on-site and to conduct a large number of experiments and measurements. In the course of the 2019 and 2020 seasons, there was no additional winterer dedicated to the EDEN ISS facility.

In 2019, a team of five people (the station leader, a geophysicist, the cook, and, in off-nominal events, the radio operator and the electrician) and in 2020 the whole new wintering crew of nine (the radio operator, two geophysicists, the cook, the meteorologist, the electrician, the air chemist, and, in off-nominal events, the mechanic and the station leader) volunteered to be involved in the nominal operations inside the MTF. Using predefined procedures for maintaining the systems in an operable condition, such as exchanging filters or refilling tanks, but also for sowing, tending and harvesting the plants or for cleaning the greenhouse, these teams operated the MTF with the main focus to produce fresh food for consumption by the wintering crew. This enabled the possibility to investigate how a space analog greenhouse can be operated in collaboration between a remote team, the RST, and a relatively untrained OOT in Antarctica as well as to examine the related crew time, workload, and operation processes [35].

As depicted in Figure 3.2, the cultivation of plants in the greenhouse started in 2019 winter season, approximately three months after the SMT 2018/2019 left the NM III. This was done because DLR wanted to investigate the option of restarting the systems of the MTF from the MCC after a hibernation phase lasting more than 2.5 months [35, 135], which ended on 06.05.2019 with first activities of the on-site operators inside the facility. The startup of all the systems in the MTF after the hibernation phase was on 16.05.2019, with the initial seeding performed two days later by the OOT 2019. In contrast to that, the work in the greenhouse in the 2020 winter season already started right after the last member of the SMT 2019/2020 left the NM III. The OOT 2020 started with a fully functional greenhouse since the initial seeding was already carried out with the SMT 2019/2020 on 02.01.2020 during the 2019/2020 summer season.

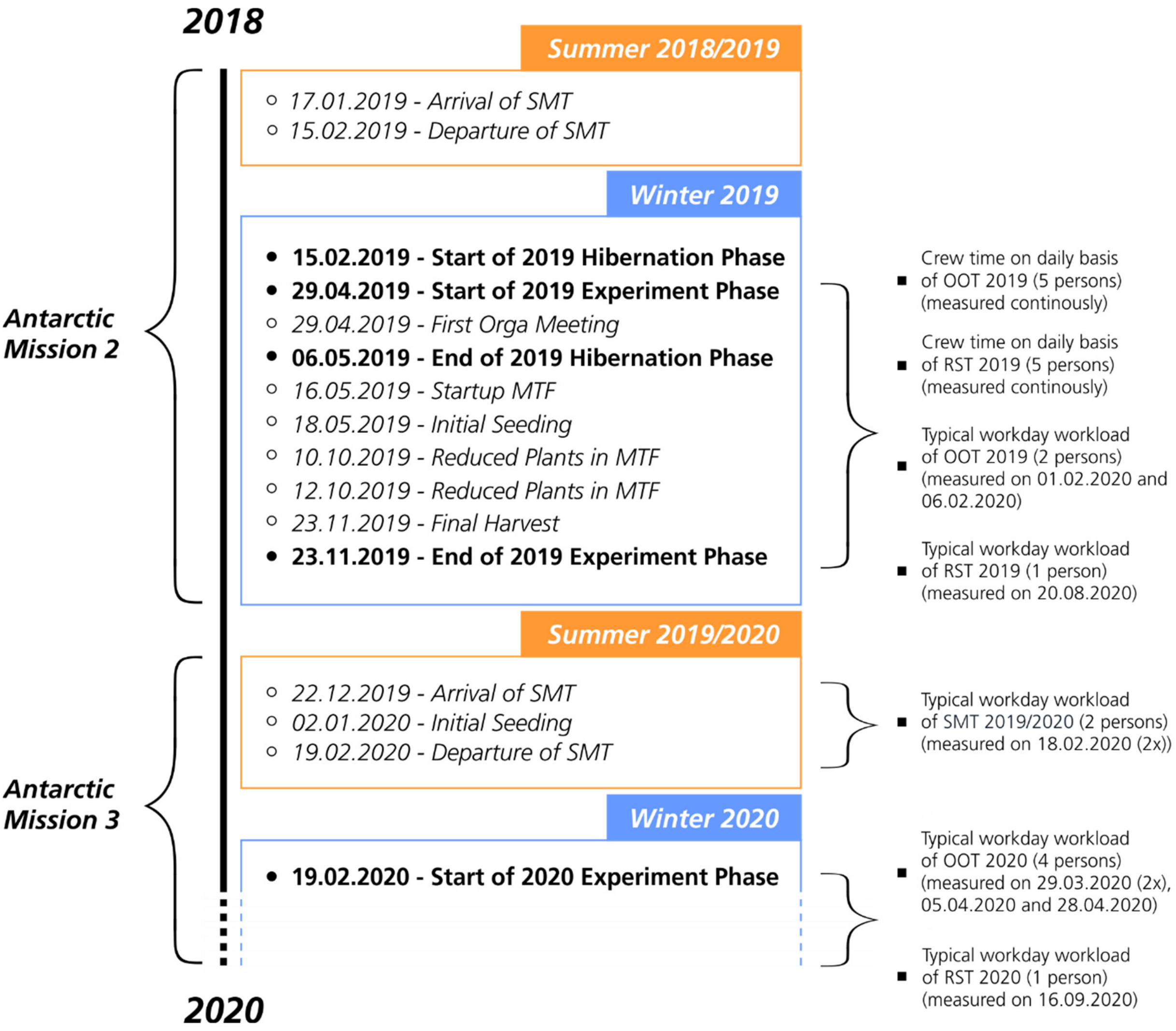


Figure 3.2: Overview of the EDEN ISS mission timeline with information about the measurements on the right side (blank bullet points representing specific moments in time; solid bullet points representing start/end points of phases). SMT = on-site summer maintenance team; RST = remote support team; OOT = on-site operator team; MTF = Mobile Test Facility.

The OOT in Antarctica is always supported remotely by the RST in the MCC. From there, it is possible to remotely control all systems of the MTF. In addition, the readings of the various sensors of the system, as well as images of the plants, are visualized on screens in the MCC [34, 94]. One person in the RST is always the main point of contact for the OOT. Nevertheless, the other RST members support with their specific expertise (e.g., structure, horticulture, or control systems) as required. The RST analyze the available information and come up with strategies and tasks to optimize the plant growth in the MTF. In regular nominal meetings with the OOT, the tasks for the following weeks are communicated and presented in a schedule planned by the RST with notes regarding the priority of the activities. The OOT mostly carries out the planning in terms of when they do specific tasks in that week, based on local conditions such as weather conditions and other activities related to the operations of the NM III. The OOT also has the possibility in the meetings to report about the past days and discuss open points regarding the MTF operations.

Between nominal meetings, the OOT and the RST are in active communication (also on weekends) about questions the OOT may have regarding the greenhouse and the status of the operations in the MTF or in case of off-nominal events such as failures of equipment or issues with the plants. In such off-nominal events, an automated email is sent to the RST and to the OOT with information about the issue. The RST then checks the telemetry data of the MTF and reaches out to the OOT. Normally, the OOT examines the event on-site and the encountered issues are reported back to the RST. The RST then develops a procedure to resolve the issue, which is executed by the OOT afterwards. Communication is done via text messages, including image transfer, emails, and telephone or videoconferencing calls, depending on the topic and the time criticality.

A typical workday of the RST 2019 and the OOT 2019 is shown in Table A.1 and Table A.2 in Appendix A.

3.3.2 Remote Support Crew Time Categorization

To better analyze, understand and visualize the crew time of the RST 2019 needed for their tasks related to the support activities of the OOT 2019, a general categorization of their support tasks is required. The investigation of the crew time values of the RST 2019 showed that their tasks could be clustered into the following six categories. These categories are based on the regularly performed tasks carried out in the MCC and are distinguished by type of task (e.g., recurring or non-recurring tasks), scope of work, and by the fact that the task is scheduled or unscheduled:

- **Nominal Meetings:** Tasks related to weekly or bi-weekly scheduled meetings via teleconference/videoconference between the RST and the OOT. They are utilized to discuss the status of the greenhouse, plan the tasks for the following week, and discuss open questions regarding the operations of the greenhouse.
- **Housekeeping:** Tasks related to daily screening of the telemetry data of the greenhouse, such as sensor and actuator data in the MCC and adjusting setpoints required to control the greenhouse to optimize the growth inside the greenhouse. Telemetry data and pictures from the plant observation cameras are used to plan upcoming tasks.
- **Nominal Support:** All planned tasks related to the greenhouse operations for which the OOT requires support from the RST. These tasks incorporate scheduled exchange of equipment/filters, preparation of new working procedures, planning of germination and harvesting dates, and clarifying questions of the OOT, such as regarding plant cultivation or function of systems (excluding science-related tasks). No immediate action is needed.

- **Off-nominal Support:** Tasks that occur unexpectedly and cannot be planned in advance, such as an exchange of broken equipment or a failure in the control system. Immediate action is required.
- **Organization Next Mission:** Tasks related to planning the next summer and winter season at the NM III. This incorporates planning system improvements and schedules, adjustment of procedures, planning of experiments, purchasing equipment, and shipping equipment.
- **Science Support:** All scheduled tasks related to science activities done in the greenhouse where the OOT needs support by the RST (not applicable for the 2019 experiment phase and thus not considered in the following). No immediate action is required.

The established remote support task categories can be used as a generic set of definitions for future planetary surface greenhouse concepts.

3.3.3 Participants

A summary of the characteristics of the study participants for the crew time and workload measurements is listed in Table 3.3, with corresponding detailed descriptions in the following.

Table 3.3: Characteristics of the study participants for the crew time and workload measurements. MTF = Mobile Test Facility.

Participant Group	Measurements	Group Composition	Experiences
Remote Support Team 2019	Crew time	5 DLR employees	• experts regarding systems and procedures inside MTF
	Workload	1 DLR employee	
Remote Support Team 2020	Workload	1 DLR employee	• expert regarding systems and procedures inside MTF
On-site Summer Maintenance Team 2019/2020	Workload	2 DLR employees	• experts regarding systems and procedures inside MTF
On-site Operator Team 2019	Crew time	5 people of the 2019 wintering crew	• not horticultural experts • unfamiliar with MTF systems • no operational experience in operating a greenhouse • received basic system training of three days (w/o plants)
	Workload	2 people of the 2019 wintering crew	
On-site Operator Team 2020	Workload	4 people of the 2020 wintering crew	• not horticultural experts • unfamiliar with MTF systems • no operational experience in operating a greenhouse • received basic system training of nine days (with plants)

Crew Time

During the 2019 winter season, the RST 2019, consisting of five DLR employees, tracked their working time needed to operate the MTF together with the OOT. All members of the RST 2019 were experts regarding the systems and procedures inside the MTF. They contributed to the development and operations of the facility from the beginning of the EDEN ISS project and gathered additional expertise in the course of the maintenance work in the MTF during the summer seasons. One expert even wintered in Antarctica during the 2018 winter season as MTF on-site operator.

The five members of the OOT 2019 who worked in the MTF during the 2019 winter season, also tracked their time required for their work in the MTF. The wintering crew members of the OOT 2019 were not horticultural experts and were unfamiliar with the systems of the MTF prior to their mission, nor did they have operational experience in operating a greenhouse. Additionally, though they received basic system training from the SMT 2018/2019, during three days at the end of the 2018/2019 summer season, this did not include practical work on plants.

Workload

Four different participant groups operating the MTF were surveyed about their workload. Three of the groups comprised people who have worked in the MTF on-site, i.e., the SMT 2019/2020, the OOT 2019, and the OOT 2020. The fourth participant group (RST 2019 + 2020) was also involved in the operation process but worked on planning and supporting the work inside the MTF remotely from the MCC.

The first evaluation group, the SMT 2019/2020, was comprised of two DLR employees who can be considered as experts regarding all systems and procedures in the MTF. They were involved in the development of the whole facility [18] and the testing phase in Bremen in 2017 [34] as well as in the operation process since 2018 [34, 35].

The second group included two participants of the five OOT 2019 members who worked in the MTF during the 2019 winter season.

The third investigation group included four participants of the nine OOT 2020 members who worked in the MTF during the 2020 winter season. Due to the fact that the initial seeding was already done during the 2019/2020 summer season together with the SMT 2019/2020 (Figure 3.2), it was possible, in contrast to the 2019 winter season, to train the OOT 2020 in the interaction with the plants (e.g., sowing, transplanting or harvesting) in addition to the basic system training provided at the end of the summer season. In total, the OOT 2020 received nine days of training, including safety briefings, from the SMT 2019/2020. Nevertheless, they were not horticultural experts and were unfamiliar with the systems of the MTF prior to their mission, nor did they have operational experience in operating a greenhouse.

The fourth group comprised two DLR employees, of whom one was the main responsible person of the RST 2019 mentioned in Subsection 3.3.3 and the other of the RST 2020. Both participants can be described as experts regarding the systems and procedures inside the MTF since they contributed to the development of the facility from the beginning of the EDEN ISS project, with additional experience of several stays in Antarctica as part of the SMTs and one expert even wintered in Antarctica during the 2018 winter season as the MTF on-site operator.

3.3.4 Measurement Collection

Crew Time

The crew time in 2019 was measured during the 209 days of the 2019 experiment phase (Figure 3.2). There were no crew time measurements for the 2020 winter season.

The RST 2019 tracked their crew time for every specific task manually, using a watch or smartphone, and individually for every team member of the RST. The gathered information was documented in an Excel spreadsheet after a task was executed, with additional information about observations or other relevant notes. This was done for each day during the 2019 experiment phase. No tasks related to remote support were conducted by the RST after 12.11.2019. Nevertheless, the MTF was still in operation until the final harvest during the 2019 experiment phase (Figure 3.2).

In contrast to the RST 2019, the OOT 2019 manually tracked their crew time for the sum of all activities per day, using a watch or smartphone. All daily activities were filled into an Excel spreadsheet at the end of the workday in the MTF, together with additional information about observations or other relevant notes and total time needed for all tasks performed by the specific OOT 2019 members on that day. This was done for each day between 01.06.2019 and the day of the final harvest during the crew time experiment phase (Figure 3.2). The crew time between 29.04.2019 and 31.05.2019 was estimated based on single point measurements during this period as well as on the average value of the measured crew time needed for the work in the MTF between 03.06.2019 (start of week 6 of the experiment phase) and 13.10.2019 (end of week 24 of the experiment phase). All crew time values include the 400 m walk from the NM III to the MTF and back. The time needed for the walk between NM III and MTF can range from 5-20 min each way, depending on the weather conditions [48]. For some specific tasks, crew time values were documented in detail.

The time needed to perform all crew time measurements, such as looking at the watch and documenting timespans, was not considered. This was done because it was only in the range of a few seconds and, for that reason, considered insignificant.

Workload

To get an overview of all workload aspects related to operations of a space analog greenhouse and to find potential possibilities for improvement of the workload, the NASA TLX is used in this work. The NASA TLX is a multi-dimensional rating procedure that comprises six dimensions to assess the workload from one or more operators: mental demand, physical demand, temporal demand, own performance, effort, and frustration [53, 54].

The NASA TLX was originally developed for application in aviation and is used nowadays for a broad spectrum of use-case scenarios, such as the assessment of factors relevant to successful performance (e.g., teamwork, crew size, fatigue, and stress) or the interface design/evaluation of visual and auditory displays, vocal and manual input devices, as well as virtual and augmented vision. [55]

NASA TLX is a retrospective measure in which participants rate a specific task after its execution using a multi-dimensional rating scale. These dimensions are rated by the participants on a 20-point bipolar scale, which ranges from a score of 0 to 100 (in increments of five). To calculate an overall workload score out of the six rating scale scores (raw ratings), a weighting procedure is used to calculate weights. For this purpose, a pairwise comparison is conducted by the participants subsequent to the rating of the six dimensions. The raw ratings and the weights are subsequently processed to adjusted ratings and eventually to an overall workload score with a value ranging from 0 to 100. [53, 56, 136]

The SMT 2019/2020 worked 60 days in Antarctica during their summer season (Figure 3.2). They assessed their workload at the end of their summer season on 18.02.2020 (two participants). The two members of the SMT 2019/2020 worked together approximately 16 CM-h day^{-1} in the greenhouse, including weekends and holidays.

The two participants of the five OOT 2019 members worked on MTF related tasks during the 209 days of the 2019 experiment phase (Figure 3.2). They assessed their workload on-site in Antarctica near the end of the 2019/2020 summer season on 01.02.2020 (one participant) and 06.02.2020 (one participant). Their amount of time spent at the greenhouse sums up to approximately 2.6 CM-h day^{-1} over this period. During the period when the greenhouse was full of mature plants, this value was approximately 3 CM-h day^{-1}.

The four participants of the nine OOT 2020 members worked approximately 2 CM-h day^{-1} on MTF related tasks. This group assessed their workload in the first month of the 2020 winter season on 29.03.2020 (two participants), 05.04.2020 (one participant) and 28.04.2020 (one participant). This was done to create a group of participants who were newly trained and just starting to get familiar with the work processes. On 19.02.2020, the last member of the SMT 2019/2020 left the NM III and handed over a fully functional MTF, with plants inside, to the OOT 2020. This date was chosen as starting date for the 2020 experiment phase and for the assessment of the workload of the OOT 2020 with respect to activities related to the MTF in the course of the 2020 winter season.

The workload of the RST 2019 was assessed on 20.08.2020 (one participant) for their remote support during the 2019 experiment phase (209 days) and the workload of the RST 2020 on 16.09.2020 (one participant) for the remote support during the, at that time still ongoing, 2020 experiment phase. Even though the assessment was carried out for two different experiment phases, the average of the results is presented in Subsection 3.4.2 since the tasks executed by both groups are similar.

3.4 Results

3.4.1 Crew Time

Table 3.4 shows the crew time development on a monthly basis for the OOT 2019 and the RST 2019 using the described remote support task categories over the course of the 2019 EDEN ISS experiment phase.

Table 3.4: Crew time (CT) development over the course of the 2019 EDEN ISS experiment phase on a monthly basis for the on-site operator team (OOT) 2019 and the remote support team (RST) 2019. Values marked with [a] are estimated based on single point measurements and on the average value of the measured crew time needed for the work in the Mobile Test Facility between 03.06.2019 and 13.10.2019.

Time Period	**CT for RST 2019 [CM-h]**							**CT for OOT 2019 [CM-h]**	**Overall CT w/o Orga Next Mission [CM-h]**
	Nominal Meetings	**House-keeping**	**Nominal Support**	**Off-nominal Support**	**Orga Next Mission**	**Total w/o Orga Next Mission**	**Total w/ Orga Next Mission**		
April	0.75	0	0.75	0	0	**1.50**	**1.50**	[a] **0.75**	**2.25**
May	6.00	5.00	11.25	4.25	4.00	**26.50**	**30.50**	[a] **65.75**	**92.25**
June	9.75	2.25	5.00	14.00	5.00	**31.00**	**36.00**	**98.25**	**129.25**
July	12.00	5.50	8.75	9.25	10.25	**35.50**	**45.75**	**102.00**	**137.50**
August	12.00	6.25	0.75	8.75	22.00	**27.75**	**49.75**	**109.00**	**136.75**
September	6.75	2.25	0.50	0	32.50	**9.50**	**42.00**	**76.25**	**85.75**
October	5.50	0.50	1.50	2.50	1.00	**10.00**	**11.00**	**57.50**	**67.50**
November	0.75	0	0	3.50	14.00	**4.25**	**18.25**	**39.00**	**43.25**
Yearly Total	**53.50**	**21.75**	**28.50**	**42.25**	**88.75**	**146.00**	**234.75**	**548.50**	**694.50**

The crew time for the RST 2019 can be divided into 53.5 CM-h needed for nominal meetings, 21.75 CM-h for housekeeping activities, 28.5 CM-h for nominal support, and 42.25 CM-h for off-nominal support. This sums up to a total crew time of 146 CM-h for the RST 2019, not considering the organizational work for the next mission. Adding the crew time of 88.75 CM-h for the organizational work for the next mission, the total crew time for the RST 2019 increases to 234.75 CM-h. Dividing these values by the 30 weeks of the 2019 experiment phase, the average amount of approximately 4.9 CM-h week^{-1} (without the organizational work for the next mission) and 7.8 CM-h week^{-1} (including the organizational work for the next mission) can be calculated. By far the highest crew time amount occurred related to organizational work for the next mission, followed by the crew time needed for the nominal meetings. Crew time dedicated to off-nominal support is on the third rank. The crew time needed for housekeeping and nominal support is nearly the same and has the lowest value for the RST 2019.

The total crew time for the OOT 2019 adds up to 548.5 CM-h or approximately 18.3 CM-h week^{-1} using the 30 weeks of the 2019 experiment phase. This amount is almost four times higher than the amount of crew time needed for the remote support in 2019, without the crew time for the organizational work for the next mission, and more than double the total amount of the remote support crew time in 2019, when including the crew time for the organizational work for the next mission. For the period where the greenhouse was full of mature plants, which was between 03.06.2019 and 13.10.2019, a weekly crew time for the OOT 2019 of approximately 21.3 CM-h can be calculated.

The overall crew time needed for operating the EDEN ISS greenhouse during the 2019 experiment phase, meaning the sum of the crew time of the RST 2019 (without organizational work for the next mission) and of the OOT 2019, is 694.5 CM-h or approximately 23.2 CM-h week^{-1}.

Monthly and Weekly Development

In Figure 3.3 and Figure 3.4, the development of the crew time over the course of the 2019 experiment phase is shown on a monthly, respectively weekly, basis for the OOT 2019 and the RST 2019.

It can be derived from Figure 3.3 that the total crew time development over the course of the 2019 EDEN ISS experiment phase for the RST 2019 and OOT 2019 on a monthly basis shows a similar trend (see also Table 3.4). Because the 2019 experiment phase started on 29.04.2019, crew time values for April are almost zero. The crew time values for the OOT 2019 increase during the first months of operations to a maximum of 109 CM-h month^{-1} in August. Nevertheless, it can be seen that the values between June and August are quite similar and range between 98.25 and 109 CM-h month^{-1} (see also Table 3.4). The lower value in May of 65.75 CM-h can be explained by the fact that the actual startup of all the systems in the MTF occurred on 16.05.2019, with the initial seeding two days later (week 3 in Figure 3.4). Only preparation work for the startup of the system was performed at the beginning of May. Younger plants in the first months resulted in less work. Also, the monthly RST 2019 crew time (without organizational work for the next mission) increased during the first months of operations due to the reasons mentioned previously. In difference to the OOT 2019 crew time, it reached a maximum of 35.5 CM-h month^{-1} already in July. This development can also be seen in Figure 3.4, with an increase in crew time from week 1 to week 15 (beginning of August). Nevertheless, the RST 2019 crew time values were in a similar range between week 2 and week 17, when not considering crew time for off-nominal events and organizational work for the next mission (Figure 3.3 and Figure 3.4).

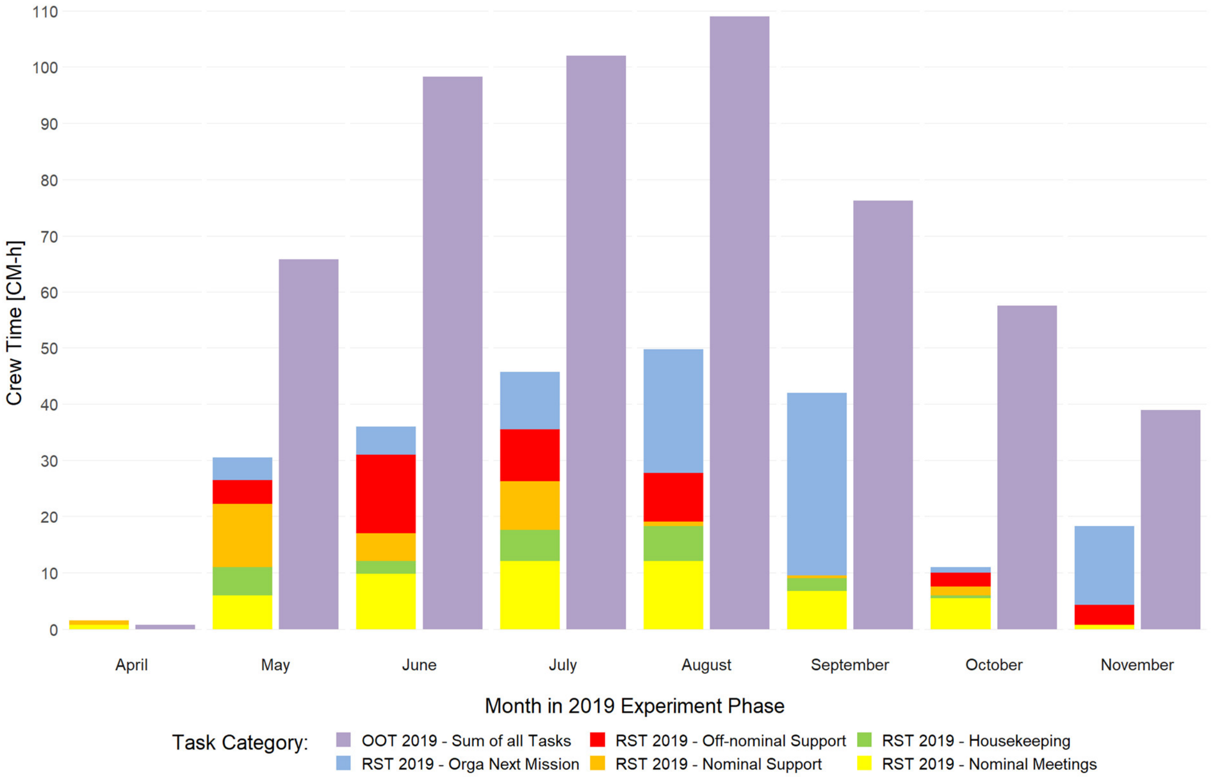


Figure 3.3: Crew time development over the course of the 2019 EDEN ISS experiment phase on a monthly basis for the on-site operator team (OOT) 2019 and the remote support team (RST) 2019. The on-site operator team's crew time values for April and May are estimated based on single point measurements and on the average value of the measured crew time needed for the work in the Mobile Test Facility between 03.06.2019 and 13.10.2019.

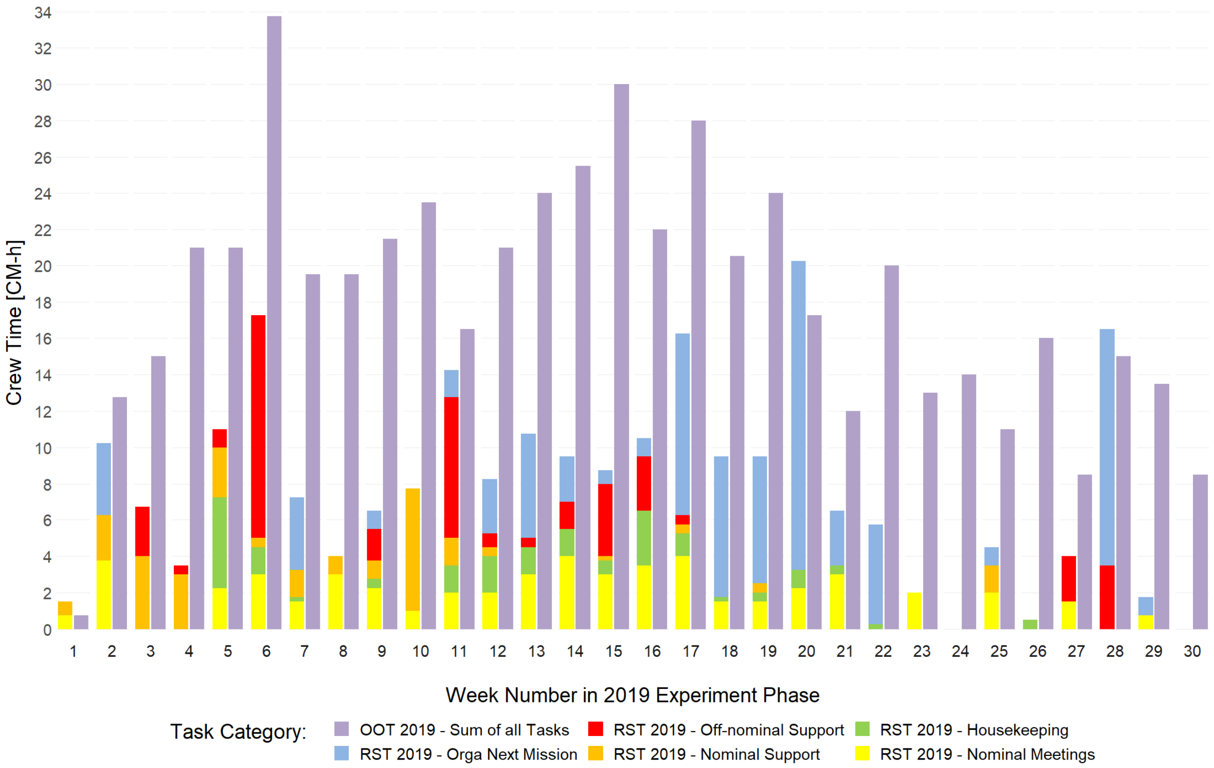


Figure 3.4: Crew time development over the course of the 2019 EDEN ISS experiment phase on a weekly basis for the on-site operator team (OOT) 2019 and the remote support team (RST) 2019. The on-site operator team's crew time values for April and May are estimated based on single point measurements and on the average value of the measured crew time needed for the work in the Mobile Test Facility between 03.06.2019 and 13.10.2019.

Only week 6 in Figure 3.4 shows a higher crew time amount of 33.75 CM-h week^{-1}, which is also the maximum value of all weeks of the 2019 experiment phase. During that week, the OOT 2019 had to counteract a massive growth of biofilm inside the nutrient solution and in the nutrient lines, which resulted in a lot of work to clean the system. In addition, a failure of the thermal control system occurred, which had to be handled as quickly as possible to keep the plants alive. The free cooler valve of the thermal control system was frozen and stuck in the open position. As a consequence, the internal cooling loop was getting too cold, causing problems with the cooling of the LED system inside the greenhouse. The OOT 2019, supported by the RST 2019, solved the issue by fixing the power connector inside the valve actuator.

Also, in week 11 (Figure 3.4), a series of time-consuming off-nominal events occurred. The RST 2019 lost the remote connection to the control system in Antarctica. Furthermore, the daily plant images were not transferred to the MCC due to a defective plant observation camera. Both issues were solved by collaboration between the radio operator at NM III and the RST 2019. Another off-nominal event in this week was caused by a failure in the readings of an electrical conductivity (EC) sensor, causing the nutrient delivery system to overdose the nutrient solution with fresh water and nutrient stock solution alternately, eventually resulting in an empty fresh water tank and base canister, which needed to be refilled. A software fix solved the issue. The last event in that week was an overflow of the nutrient solution tank caused by human error while conducting the maintenance of the nutrient solution lines in the greenhouse. Finding the source of a failure always took a lot of time and communication between the OOT 2019 and the RST 2019. Also, the significant effect of the off-nominal events in week 6 and week 11 on the RST 2019 crew time can be seen in Figure 3.4. It can be seen that the OOT 2019 crew time in week 11 is still smaller than the corresponding crew time in week 10 or 12. This could be explained by the fact that the control and data handling system-related off-nominal events in week 11 had a bigger effect on the RST 2019 crew time and could be solved mostly remotely.

Starting at week 16 (mid-August), the weekly crew time of the OOT 2019 decreased (see also September to November in Figure 3.3). This can be related to the fact that the OOT 2019 became more familiar with the system and the procedures inside the MTF over the course of time, which also resulted in greater overall independence from the support of the RST 2019 regarding the work in the MTF. Also, the weekly nominal meeting was changed to a bi-weekly meeting starting at the end of September since this was considered sufficient for the operations of the MTF (e.g., fewer things to discuss). In addition, the number of plants was reduced in week 24 (Figure 3.2) to allow the OOT 2019 to dedicate more time to the preparation of the next summer season, which obviously also contributed to a lower crew time related to work in the MTF at the end of the 2019 experiment phase. All these incidents also affected the RST 2019 crew time in a similar way. In August, the RST crew time value decreased already to 27.75 CM-h month^{-1} with a high reduction of crew time in September (9.5 CM-h month^{-1}), October (10 CM-h month^{-1}), and November (4.25 CM-h month^{-1}).

The crew time needed for the nominal support category was approximately around 8.3 CM-h month^{-1} during the first months (May to July) and decreased to approximately 0.7 CM-h month^{-1} for August to November. In addition, the crew time for the nominal meeting category increased to a maximum of 12 CM-h month^{-1} in July and August. It decreased afterwards, also because of the transition from weekly to bi-weekly nominal meetings. The crew time needed for the housekeeping category was also higher in the beginning, with an average value (May to August) of approximately 4.75 CM-h month^{-1}. From September to November, the average value decreased to approximately 0.9 CM-h month^{-1}. Considering the organizational work for the next mission, it can be seen that the crew time for this category increased until September since all equipment had to be shipped, and all planning activities had to be accomplished by the end of September. Nevertheless, there were some additional last-minute activities in November related to the next mission.

Analysis of Time Shares

Figure 3.5 shows the development, on a weekly basis, of the time shares of the total crew time for the OOT 2019 and the RST 2019 (without organizational work for the next mission) related to the overall crew time over the course of the 2019 experiment phase. Figure 3.5 implies that the time shares of the total crew time for the RST 2019 regarding the overall crew time were higher in the first half of the 2019 experiment phase with values between 14% and 34% (average of 28%). There is one outlier in week 1 (67%) due to preparation activities of the RST 2019 for 2019 experiment phase and a second outlier in week 11 (44%) due to a previously described bigger off-nominal event.

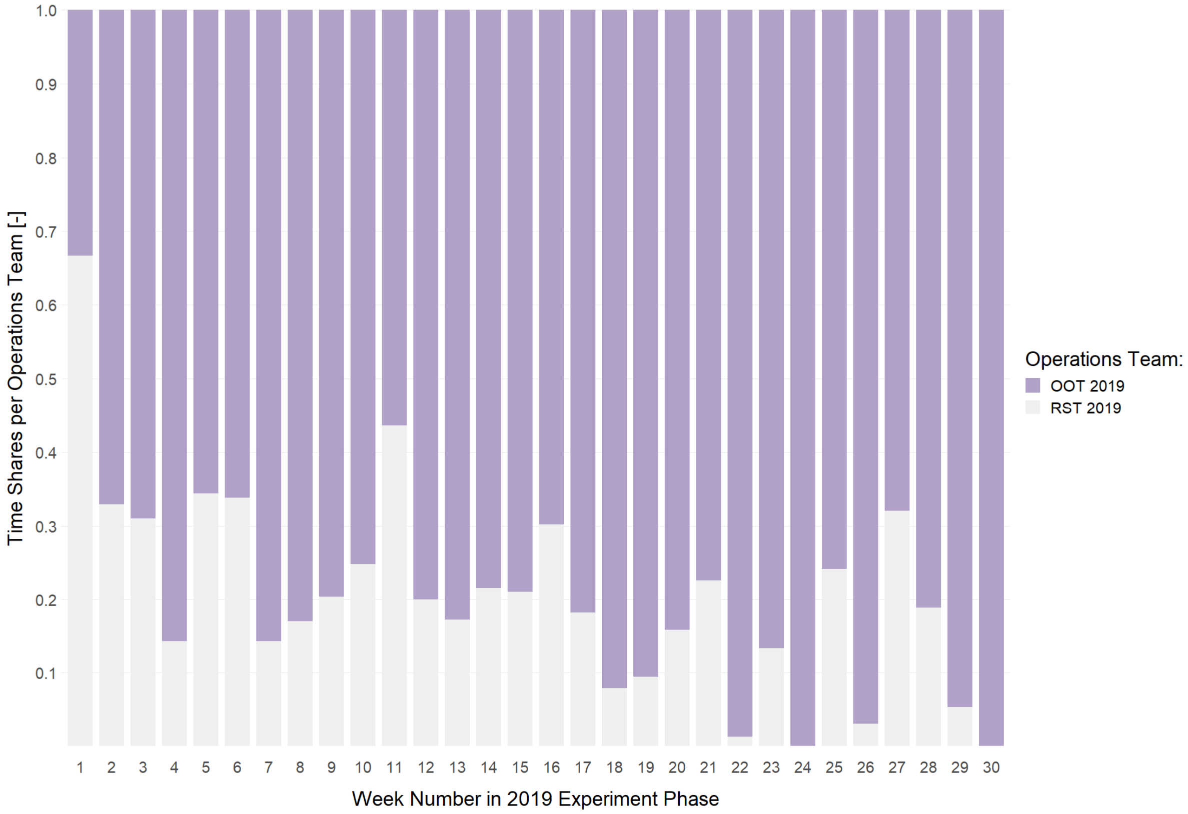


Figure 3.5: Development over the course of the 2019 EDEN ISS experiment phase on a weekly basis for the time shares of the total crew time for the on-site operator team (OOT) 2019 and the remote support team (RST) 2019 (without organizational work for the next mission) related to the overall crew time. The on-site operator team's crew time values for April and May are estimated based on single point measurements and on the average value of the measured crew time needed for the work in the Mobile Test Facility between 03.06.2019 and 13.10.2019.

In the second half of the 2019 experiment phase, starting at week 16, the time shares of the total crew time for the RST 2019 are between 0% and 32% (average of 13%). The values fluctuated based on events in the greenhouse, such as additional nominal support in week 25 (planning of on-site tasks for the rest of the 2019 experiment phase) or off-nominal events in weeks 27 and 28, in which more remote support was needed and hence higher RST 2019 time shares were reached.

The average value for the time shares of the total crew time for the RST 2019 (without organizational work for the next mission) during the whole 2019 experiment phase is 21%. The trend derived from Figure 3.5 reflects the learning curve of the OOT 2019 and the fact that there was a higher need for support by the RST 2019 at the beginning of the 2019 experiment phase. This can also be seen in the reduction by 61% of total crew time values of the RST 2019 from 104.75 CM-h (7 CM-h week^{-1}) during the first 15 weeks to 41.25 CM-h (2.75 CM-h week^{-1}) during the last 15 weeks. For the OOT 2019, the reduction of the total crew time values between the first 15 weeks with a value of 305.25 CM-h (20.35 CM-h week^{-1}) and the last 15 weeks with a value of 243.25 CM-h (16.22 CM-h week^{-1}) is lower, but still significant at roughly 20%.

The development, on a weekly basis, of the time shares for the categorized RST 2019 crew time (without organizational work for the next mission) over the course of the 2019 experiment phase is depicted in Figure 3.6. Since the off-nominal support activities occurred randomly and are in general not predictable, they are not depicted in Figure 3.6 for further investigations.

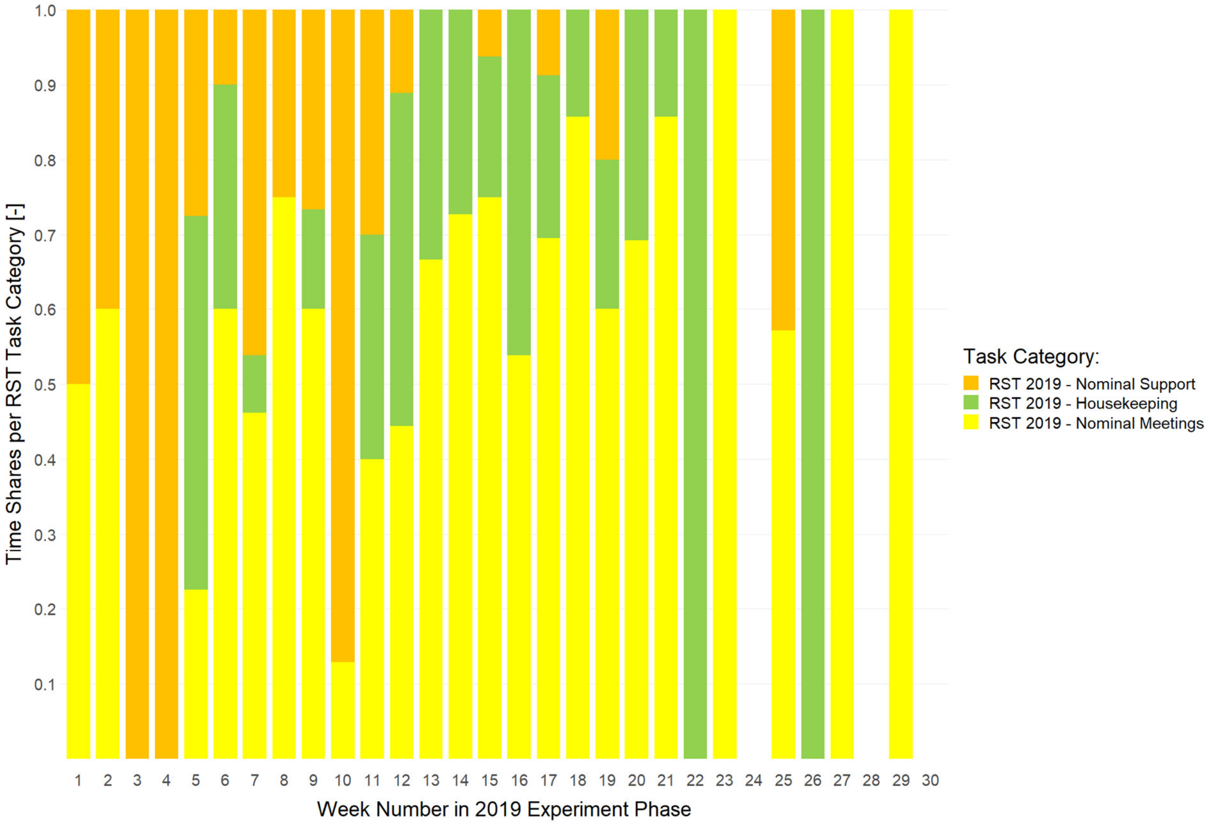


Figure 3.6: Development over the course of the 2019 EDEN ISS experiment phase on a weekly basis for the time shares per remote support team (RST) task category related to the total crew time of the remote support team 2019 (without organizational work for the next mission).

It can be seen that the time shares for the nominal support category related to the total RST 2019 crew time had the highest values in the first weeks while decreasing to a share of zero in week 13. The shares stayed around this low level until the end of the 2019 experiment phase, with smaller outliers. At the same time, the time shares for the nominal meetings continuously increased until the end of the 2019 experiment phase. It can also be derived that the time shares for the housekeeping category are relatively constant between weeks 5 and 21. This is due to the fact that there was no urgency to conduct housekeeping activities initially, as the plants were not sown or still very young. After week 21, the crew time required for housekeeping activities was nearly not needed anymore (Figure 3.4) and just emerged in weeks 22 and 26 as the only occurrences of this activity for the RST 2019 in these weeks.

Also, the trend depicted in Figure 3.6 reflects the previously mentioned learning curve of the OOT 2019. If the off-nominal support category is considered, it can be noted that these activities can have pretty high time shares in case they occur.

3.4.2 Workload

Table 3.5 shows the NASA TLX adjusted rating of dimensions and overall workload scores with standard error of the mean (SEM) for the corresponding crews on-site in Antarctica and the RST at the MCC.

Table 3.5: NASA TLX adjusted rating of dimensions and overall workload scores, including standard error of the mean (SEM), for the corresponding crews on-site in Antarctica and the remote support teams at Mission Control Center in Bremen. SMT = on-site summer maintenance team; RST = remote support team; OOT = on-site operator team.

	SMT 2019/2020 (n=2)		**OOT 2019 (n=2)**		**OOT 2020 (n=4)**		**RST 2019 + 2020 (n=2)**	
	Mean	**SEM**	**Mean**	**SEM**	**Mean**	**SEM**	**Mean**	**SEM**
Mental Demand	260.0	0	90.0	30.0	90.0	31.6	312.5	87.5
Physical Demand	32.5	17.5	85.0	35.0	131.3	70.1	0	0
Temporal Demand	337.5	37.5	157.5	7.5	170.0	56.3	362.5	62.5
Performance	12.5	2.5	112.5	7.5	70.0	17.3	30.0	0
Effort	175.0	35.0	152.5	87.5	103.8	25.1	132.5	77.5
Frustration	0	0	0	0	0	0	175.0	35.0
Overall Score	**54.5**	**3.5**	**39.8**	**5.5**	**37.7**	**5.8**	**67.5**	**4.5**

Overall Workload Score

Figure 3.7 and Table 3.5 show the overall workload score for the SMT 2019/2020, the OOT 2019 and OOT 2020 in Antarctica, as well as the RST 2019 + 2020 in the MCC. The values are derived from the averaged overall workload score of all participants of the four groups. The results of the workload measurements for the OOT 2019 and OOT 2020 show quite similar values, with 39.8 (SEM=5.5) for 2019 and 37.7 (SEM=5.8) for 2020, while the value for the SMT 2019/2020 is substantially higher with a value of 54.5 and a lower SEM of 3.5. The overall workload score for the RST 2019 + 2020 in the MCC of 67.5 (SEM=4.5) is even higher compared to the one for the SMT 2019/2020 depicted in Figure 3.7, while the SEM is a little higher.

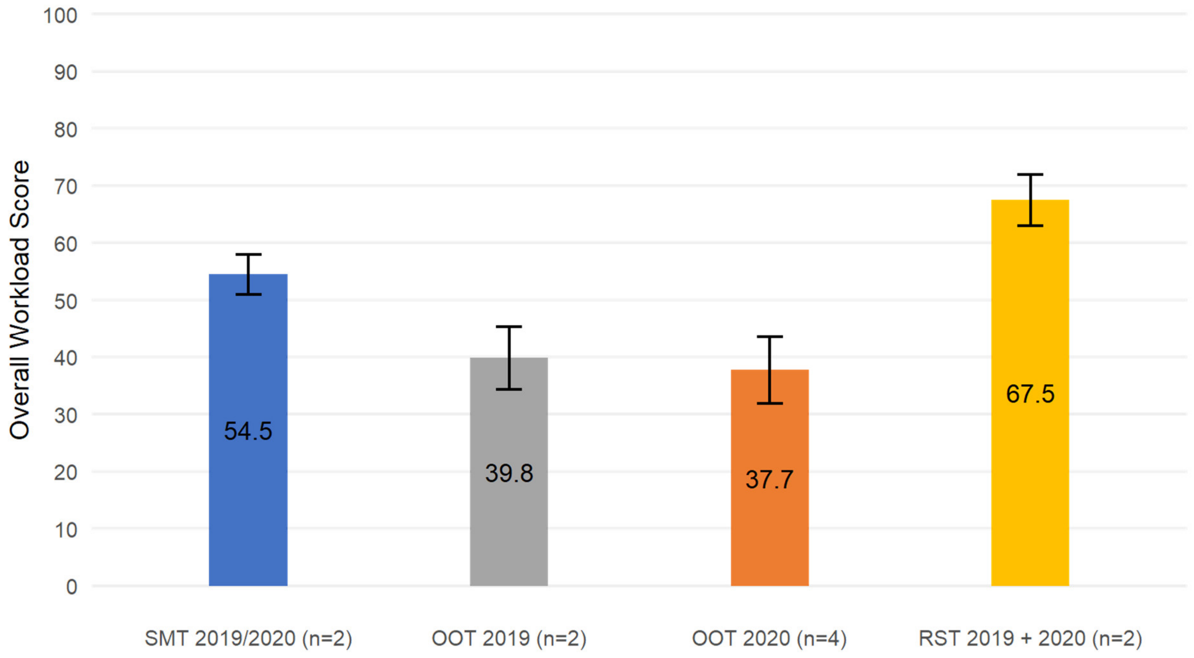


Figure 3.7: NASA TLX overall workload scores, including standard error of the mean (SEM), for the corresponding crews on-site in Antarctica and the remote support teams at Mission Control Center in Bremen. SMT = on-site summer maintenance team; RST = remote support team; OOT = on-site operator team.

Adjusted Ratings

In Table 3.5 and Figure 3.8, the adjusted ratings of the six NASA TLX dimensions for the SMT 2019/2020, the OOT 2019, the OOT 2020, and the RST 2019 + 2020 are investigated. The values are derived from the averaged adjusted ratings of all participants in the four groups.

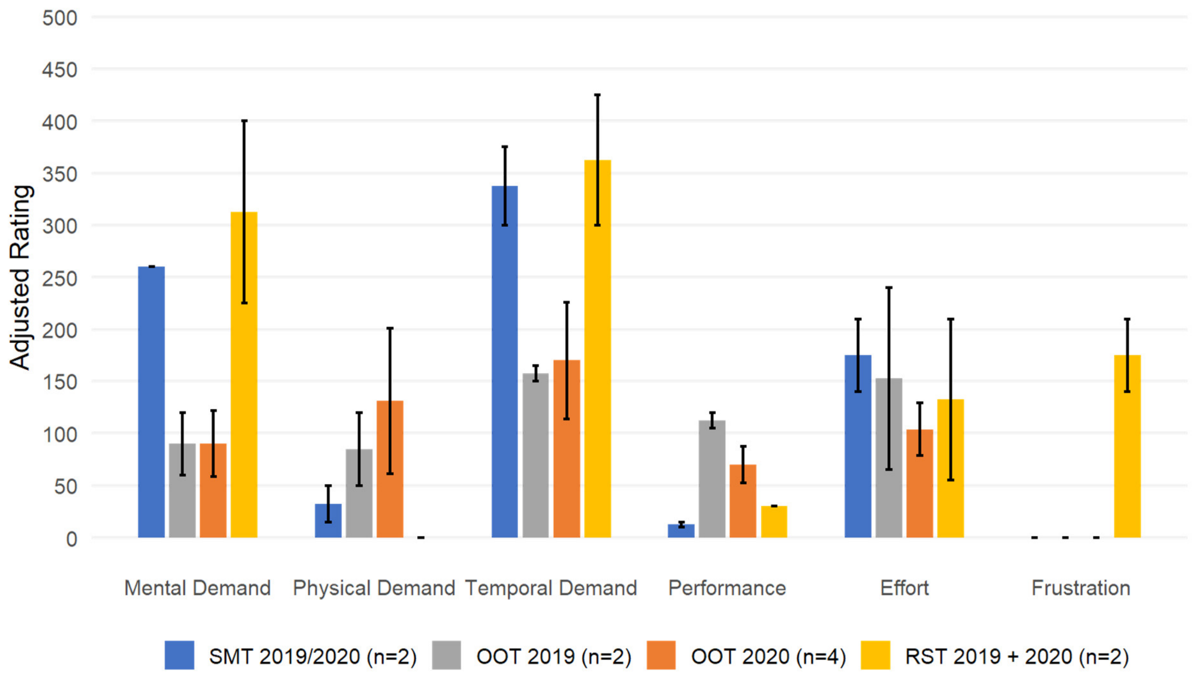


Figure 3.8: NASA TLX adjusted rating of dimensions, including standard error of the mean (SEM), for the corresponding crews on-site in Antarctica and the remote support teams at Mission Control Center in Bremen. SMT = on-site summer maintenance team; RST = remote support team; OOT = on-site operator team.

The **temporal demand** with an average score of 337.5 (SEM=37.5) for the SMT 2019/2020, 157.5 (SEM=7.5) for the OOT 2019, 170.0 (SEM=56.3) for the OOT 2020 and 362.5 (SEM=62.5) for the RST 2019 + 2020 shows the highest individual scores of all six dimensions. As can be seen, the temporal demand for the SMT 2019/2020 is much higher (second highest score in Figure 3.8) compared to the two winter groups with almost similar values. The RST 2019 + 2020 has an even higher value (highest score in Figure 3.8) compared to the value of the SMT 2019/2020.

This can be explained by the fact that the SMT 2019/2020 had a limited time frame and was subject to time pressure to fulfill all scheduled tasks during daily 16 CM-h shifts (two people each 8 h day^{-1}) in the short 2019/2020 summer season. In contrast, the OOT 2019 worked an average of 2.6 CM-h day^{-1} and the OOT 2020 2 CM-h day^{-1}. Due to the fact that the RST 2019 + 2020 was almost continuously available (also on weekends) for the corresponding OOTs in case of questions, the higher value of the RST 2019 + 2020 can be explained, even though the average crew time of approximately 4.9 CM-h week^{-1} (without the organizational work for the next mission) was lower in case of the RST 2019 compared to the OOT 2019, the OOT 2020 or the SMT 2019/2020. In addition, they had to quickly react to protect the plants in case of off-nominal events and had to resolve the occurred issue.

The **mental demand** for the SMT 2019/2020, with a value of 260.0 (SEM=0), is the second highest individual value for this group and much higher compared to the values for the OOT 2019 and the OOT 2020, which are identical with a value of 90.0 except for a difference in SEM of 30.0

and respectively 31.6. The value for the RST 2019 + 2020 for this dimension of 312.5 (SEM=87.5) is again higher (third highest score in Figure 3.8) compared to the value of the SMT 2019/2020.

The tasks conducted by the SMT 2019/2020 and the RST 2019 + 2020 were more complex and challenging compared to the rather less mentally demanding tasks of the OOT 2019 and OOT 2020 [91]. In addition, the OOTs were always remotely supported by the corresponding RSTs, who prepared the working procedures of the OOTs. This could be a reason for the lower mental demand scores of the OOT 2019 and the OOT 2020. The higher mental stress of the SMT 2019/2020 might be due to the fact that they also carried out more difficult and sometimes unexpected maintenance tasks prior to the start of the actual growing season. These tasks also included troubleshooting and addressing problems that occurred during the prior season, which were scheduled to be fixed before the next growing season. The RST 2019 + 2020 had to quickly resolve issues in case of off-nominal events, observe the MTF remotely, and plan the procedures and schedules executed by the OOT 2019 and OOT 2020 in Antarctica.

The **effort** assessment of the four groups resulted in workload scores almost in the same range. The SMT 2019/2020 has a value of 175.0 (SEM=35.0). It is only slightly higher compared to the value for the OOT 2019 of 152.5 (SEM=87.5), which is the second highest value for this group. This score is followed by the score of the RST 2019 + 2020 with a value of 132.5 (SEM=77.5). The OOT 2020 has the lowest value of 103.8 (SEM=25.1).

The small differences in the effort scores of the SMT 2019/2020 compared to the OOT 2019 and OOT 2020 can be explained by the fact that the SMT 2019/2020 conducted more demanding tasks than those performed in a fully operable greenhouse during the winter season. Furthermore, ten people, instead of five, operated the greenhouse in Antarctica during the 2020 winter season compared to the 2019 winter season. This could result in a lower value for the OOT 2020 because it was possible to divide the tasks in the MTF in 2020 between more people and decrease the individual effort.

The value for the **physical demand** for the SMT 2019/2020 is low with a value of 32.5 (SEM=17.5). The value for the OOT 2019 is higher with a value of 85.0 (SEM=35.0). The OOT 2020 has a value of 131.3 (SEM=70.1), which is the second highest value for this group. The deviation between the OOT 2020 value and the SMT 2019/2020 value is pretty high. No member of the RST 2019 + 2020 preferred physical demand over another dimension, which results in an adjusted rating value of zero (SEM=0).

The OOTs, during the winter seasons, sometimes had to walk to the greenhouse several times per day [91]. In addition, nutrient solution exchange, including cleaning the tanks and more exchange of water (fresh and waste water), was necessary. These activities were more physically demanding compared to similar tasks performed during the summer season [91] due to the rough weather conditions during the winter season (dark and really cold periods, with temperatures down to minus 43.6 °C on 01.08.2019 and 11.08.2019 as lowest temperature in that winter season). On the other hand, the RST 2019 + 2020 did not have to perform any physical work.

Considering the **performance** assessment, the SMT 2019/2020 has the second lowest value in Figure 3.8, with a value of 12.5 (SEM=2.5). The values for this dimension are much higher for the OOT 2019, with a value of 112.5 (SEM=7.5) and for the OOT 2020 of 70.0 (SEM=17.3). The value of the RST 2019 + 2020 is also quite low, with a value of 30.0 (SEM=0), which is the third lowest value in Figure 3.8.

In contrast to the OOT 2019 and OOT 2020, the SMT 2019/2020 developed, scheduled and conducted their tasks during the summer season independently. This might have resulted in an increase in their level of confidence based on performing their own tasks instead of processing pre-developed procedures as was done by both OOTs. [91] In addition, both the OOTs were relatively untrained related to work in the MTF, while the SMT 2019/2020 and the RST 2019 + 2020 developed the MTF and worked with it for a couple of years [34]. It could be that for this reason, the SMT 2019/2020 and the RST 2019 + 2020 were more confident in a positive outcome of their work and rated their performance higher.

The dimension **frustration** shows a value of zero (SEM=0) for all participants of the SMT 2019/2020, the OOT 2019, and the OOT 2020 since no participant out of these groups rated frustration over another dimension. In case of the RST 2019 + 2020, frustration is ranked in third position for this group and has a value of 175.0 (SEM=35.0).

The SMT 2019/2020 and the two OOTs could directly see the results of their work and could also positively experience the plants' growth process in a hostile environment like Antarctica. Consequently, this could reduce the frustration level for these groups in case of system failures, for example. In case of the RST 2019 + 2020, this direct feedback of their work was not possible and did not reduce the frustration level.

Overall, the SMT 2019/2020 and the RST 2019 + 2020 have the highest values in Figure 3.8, i.e., temporal demand and mental demand, as well as the lowest values, i.e., performance and physical demand. The effort scores are almost in the same range for all four groups. The frustration scores show a value of zero for the SMT 2019/2020 and both OOTs. Solely for the RST 2019 + 2020, this value is unequal to zero and rated on third position of the dimensions of this group. The differences between the highest and lowest values are significant (Figure 3.8). The overall workload values for the OOT 2019 and OOT 2020 are comparable. In addition, there are no significant differences between the dimensions for the OOTs except in case of frustration.

The results of statistical analysis using an analysis of variance (ANOVA) on the six NASA TLX dimensions have shown a statistical difference between the four participant groups for the dimension mental demand, performance and frustration. Due to the fact that the number of participants for the workload evaluation is rather small, the requirements for an ANOVA, such as normal distribution and homogeneity of variance of the residuals, were not fulfilled, and therefore, statistical conclusions based on the ANOVA cannot be reported.

3.5 Discussion and Conclusion

It is crucial to point out that workload and corresponding crew time strongly depend on the system architecture, especially with respect to maintenance procedures [48]. Due to the reasons in the following and the fact that future planetary surface greenhouse systems will deviate to some extent from the architecture of the EDEN ISS greenhouse, the crew time and workload values in this chapter can only give implications for the values, which will emerge during future planetary surface missions incorporating a greenhouse. Conversely, crew time and workload data on existing architectures can inform the further design and development activities of future greenhouses with the aim of minimizing crew time and workload. This is also applicable to the crew time values gathered at other space analog test sites on Earth [47] or onboard the ISS [41].

In case of future space missions, astronauts will operate greenhouses, which will be part of habitats installed on the Moon or Mars. The operation scenario will look different in some aspects compared to the scenario depicted in this chapter for the operations of the EDEN ISS greenhouse in Antarctica. On the Moon or Mars, the greenhouse will most likely be directly connected to the habitat, which will facilitate its access and therefore reduce the overall crew time of the greenhouse operators. This will decrease the physical demand of the operators compared to the EDEN ISS experiment phase because fresh and waste water will not be transported by hand but rather by tubes between the habitat and the greenhouse infrastructure.

Moreover, there will not be SMTs or wintering crews working in the greenhouse, but rather a habitat crew, who will be exchanged every couple of months as is done onboard the ISS or every few years in case of a Mars mission. This will be comparable to a new wintering crew described in this chapter, despite the fact that this new habitat crew would also have to carry out the maintenance work in the greenhouse, which, in case of EDEN ISS, is accomplished by the SMT. For that reason, new habitat crews will be trained on Earth in mockups of the greenhouse to be more familiar with the greenhouse systems and tasks related to plant cultivation prior to their missions.

During planetary surface missions, the communication delay needs to be considered as a difference compared to the EDEN ISS analog missions. For the Moon, this delay amounts to approximately 1.35 s for one-way and for Mars to approximately 22.2 min for one-way. Both values are calculated for the largest distance between the Earth and the Moon, or respectively Mars. In the case of the Moon, a remote support scenario could look quite similar compared to EDEN ISS due to the small communication delay. In the case of Mars, remote support by the MCC in case of nominal support or off-nominal support activities needs to be organized in a different way to account for higher communication delays. More predefined nominal and off-nominal event related procedures could be used to reduce the dependence of the astronauts on the MCC. Nevertheless, the MCC will be involved in case nominal or off-nominal support is required by the astronauts.

The 2019 experiment phase in Antarctica has shown that maintenance and repair activities hold a significant share of the total crew time for the OOT needed to operate a planetary surface greenhouse such as already reported by Schwartzkopf [102] for the BIOS-3 experiments, Russell *et al.* [45] for activities onboard the ISS and Zabel *et al.* [48] for the 2018 EDEN ISS experiment phase. Russell *et al.* [45] reported that the crew time of three astronauts on ISS for habitat maintenance accounted for 1.9 CM-h day^{-1} per crew member and 2.4 CM-h day^{-1} per crew member for a crew of two astronauts. Maintenance and repair activities always have highest priority because the survival of the astronauts will depend on habitat and greenhouse systems [41].

This implies that one way to minimize the crew time needed for the operations of future planetary surface greenhouses is to implement a higher degree of automation into the greenhouse regarding maintenance activities [47, 137]. However, higher automation with respect to plant cultivation tasks such as harvesting or transplanting would also be beneficial [102]. This would reduce the crew time and workload needed for executing the automatized activity while increasing the crew time for maintenance tasks due to a more complex system architecture [102]. Hence, a trade-off analysis prior to the installation of a more automated system has to be done to determine if crew time could be reduced by implementing the automated system. Nevertheless, not all activities related to plant growth should be automated to keep the positive effect of the plant interaction on the psychological well-being of the astronauts [23].

Another way to minimize crew time and workload is to improve the learning curve of the greenhouse operators. As mentioned previously, even if well-trained, on-site operators (astronauts) might not have detailed expertise for all required procedures during a mission and consequently need remote support from the experts on ground in the MCC. Improving the learning curve would result in astronauts reaching the point of greater independence from the RST more easily and quickly, as well as working more efficiently in earlier stages of their missions. As a result, crew time and workload caused by remote support, as well as on-site tasks, could be reduced. This could be accomplished by a broader and longer system training program for the astronauts in mockups on Earth prior to their space mission.

It is characteristic that workload is coupled to crew time and vice versa. This can be explained by the fact that one dimension of the NASA TLX is temporal demand. However, no direct relation can be drawn between workload and crew time. Although the crew time of the OOT 2019 is almost four times higher than the crew time of the RST 2019 (without organizational work for the next mission), the RST 2019 had perceived a higher workload. On the other hand, it is also characteristic that a high crew time could as well lead to high perceived workload. This indicates that crew time is not the only factor affecting the workload and that workload could also be perceived as low in case of high crew time demand. Further investigations, particularly task-specific crew time and workload assessments, would be needed to draw significant conclusions on the relationship between crew time and workload.

3.5.1 Crew Time

As mentioned previously, for the 2019 winter season, crew time was measured for every specific task individually by every team member of the RST 2019. To minimize the valuable crew time of the OOT 2019 designated for the work in the MTF, only the crew time for the sum of all activities per workday was measured in case of the OOT 2019 since the OOT operated the MTF on top of their actual tasks at NM III.

The crew time of the OOT 2019 between 29.04.2019 and 31.05.2019 was not recorded because of the previously mentioned time constraints of the OOT 2019. However, it was estimated based on single point measurements during this period and on the average value of the measured crew time needed for the work in the MTF between the start of week 6 and the end of week 24 of the 2019 experiment phase. At the end of week 24, the number of plants was reduced in the MTF since the MTF OOT 2019 needed more time for the preparation of the next summer season and work in the NM III. Consequently, the period between week 6 and the end of week 24 of the 2019 experiment phase depicts the work in the MTF when it was at full plant cultivation capacity.

Due to the fact that the crew time of the OOT 2019 was only tracked for the sum of all activities per day, it is not possible to categorize the tasks and calculate the total crew time needed for a specific category as was done for the on-site operator crew time of the 2018 winter season [48], since the tasks in the EDEN ISS MTF strongly vary during one workday (Table A.1 and Table A.2 in Appendix A for typical workdays of the RST 2019 and the OOT 2019). Nevertheless, it is possible to categorize the crew time of the RST 2019.

Due to time constraints of the RST 2020 and OOT 2020, there were no crew time measurements for the 2020 winter season. However, the set of crew time measurements during the 2019 experiment phase is sufficient for a first evaluation of the crew time of the OOT in comparison to the RST.

Crew Time and Edible Biomass Production Comparison

During the 286 days of the 2018 experiment phase, 268 kg of fresh edible biomass was produced on 12.5 m² growth area in the MTF. This results in a production rate for the 2018 experiment phase of 0.075 kg day^{-1} m^{-2}. [38] In contrast, 110 kg of fresh edible biomass was grown during the 2019 experiment phase. This amount of vegetables was produced on a growth area of 12.5 m^2 during 209 days. The resulting production rate amounts to 0.042 kg day^{-1} m^{-2}, which is almost half of the 2018 experiment phase value (Table 3.6).

Table 3.6: Fresh edible biomass output and corresponding production values for different experiments. Values marked with [a] as reported in Zabel et al. [38], values marked with [b] as reported in Patterson [134] and values marked with [c] as reported in Patterson et al. [33]. RST = remote support team; OOT = on-site operator team; SPFGC = South Pole Food Growth Chamber.

Experiment	Fresh Edible Biomass [kg]	Growth Area [m²]	Duration of Experiment [days]	Production Rate	Crew Time [CM-h]	Adjusted Production Rate	Edible Biomass per Unit Labor
EDEN ISS experiment phase in 2018 – On-site operator	[a] 268	[a] 12.50	[a] 286	[a] 0.075 kg day^{-1} m^{-2}	858.0 (21.0 per week)	0.025 kg m^{-2} CM-h^{-1}	0.31 kg CM-h^{-1} (3.20 CM-h kg^{-1})
EDEN ISS experiment phase in 2019 – OOT 2019	110	12.50	209	0.042 kg day^{-1} m^{-2}	548.5 (18.3 per week)	0.016 kg m^{-2} CM-h^{-1}	0.20 kg CM-h^{-1} (5.00 CM-h kg^{-1})
EDEN ISS experiment phase in 2019 – RST 2019					146.0 (4.9 per week)	0.060 kg m^{-2} CM-h^{-1}	0.75 kg CM-h^{-1} (1.33 CM-h kg^{-1})
EDEN ISS experiment phase in 2019 – Grand total					694.5 (23.2 per week)	0.013 kg m^{-2} CM-h^{-1}	0.16 kg CM-h^{-1} (6.31 CM-h kg^{-1})
SPFGC – On-site operator	-	[b] 22.77	-	[c] 0.130 kg day^{-1} m^{-2}	[b] 23.0 per week	-	[b] 0.80 kg CM-h^{-1}

This deviation in biomass output per area between the experiment phases in 2018 and 2019 could be partially explained by the fact that fruit-bearing crops have an initial vegetative phase where they do not produce a harvest. After reaching the generative phase, they can be harvested repeatedly. The 2019 experiment phase was 77 days shorter than the 2018 experiment phase, and so the vegetative phase of the fruit-bearing crops took up a higher portion of the experiment phase. As a result, the yield from these crops could be comparatively lower than in the 2018 experiment phase. Thus, the biomass output per area could also be lower.

Moreover, there was an additional wintering crew member at NM III dedicated to the operations of the greenhouse during the 2018 experiment phase. This on-site operator from DLR worked 3 CM-h day^{-1} (858 CM-h during the whole 2018 experiment phase) in the greenhouse. In this crew time value, plant cultivation and system maintenance activities are included, but no repair and scientific activities are incorporated. The on-site operator was familiar with the system and the cultivation tasks needed prior to the 2018 experiment phase. If this value is considered in the production rate, an adjusted value of 0.025 kg m^{-2} CM-h^{-1} corresponding to 0.31 kg CM-h^{-1} (3.2 CM-h kg^{-1}) edible biomass per unit labor can be calculated.

During the 2019 experiment phase, on the other hand, no additional wintering crew member was dedicated to the greenhouse tasks, and the OOT 2019, who was unfamiliar with the systems and plant cultivation inside the MTF, operated the greenhouse in addition to their other common tasks in the NM III. In addition, the cultivated cultivars differed between the experiment phases in type and arrangement, and the number of plants was drastically reduced at the end of the 2019 experiment phase to enable the OOT 2019 to take care of their NM III preparation tasks for the following summer season.

The OOT 2019 worked approximately 18.3 CM-h $week^{-1}$ on average (548.5 CM-h during the whole 2019 experiment phase) in the greenhouse. Considering this for the production rate, an adjusted value of 0.016 kg m^{-2} CM-h^{-1} corresponding to 0.2 kg CM-h^{-1} (5 CM-h kg^{-1}) edible biomass per unit labor can be calculated. This value is still smaller than the one of the 2018 experiment phase. However, in contrast to the 2018 experiment phase, the crew time values of the 2019 experiment phase also include the repair activities conducted in the greenhouse and the walk from the NM III to the MTF and back. The adjusted production rate only considering the RST 2019 total crew time of 146 CM-h during the whole 2019 experiment phase (without organizational work for the next mission) can be calculated to 0.06 kg m^{-2} CM-h^{-1} corresponding to 0.75 kg CM-h^{-1} (1.33 CM-h kg^{-1}) edible biomass per unit labor. The value for the sum of the total crew time of RST 2019 and OOT 2019 of 694.5 CM-h during the whole 2019 experiment phase (without organizational work for the next mission) can be calculated to 0.013 kg m^{-2} CM-h^{-1} corresponding to 0.16 kg CM-h^{-1} (6.31 CM-h kg^{-1}) edible biomass per unit labor.

The SPFGC had a production rate of 0.130 kg day^{-1} m^{-2} [33]. This rate is higher than the values of the MTF during the experiment phases in 2018 and 2019. The SPFGC operator worked 23 CM-h $week^{-1}$ in the greenhouse with a growth area of 22.77 m^2 inside the Amundsen-Scott South Pole station [134]. Patterson [134] reported a 0.8 kg CM-h^{-1} edible biomass per unit labor. The corresponding value with 0.2 kg/CM-h for the 2019 EDEN ISS experiment phase is four times smaller.

The difference between the values from the SPFGC and the 2019 EDEN ISS experiment phase can be explained by similar reasons mentioned previously for the comparison with the 2018 EDEN ISS experiment phase. Also, in the SPFGC, a dedicated on-site operator was responsible for the activities related to the greenhouse [33]. Moreover, crew time required for repairs and maintenance activities for primary hardware systems, as well as crew time of volunteers, was not considered for the operations of the SPFGC [134]. Due to the fact that the SPFGC was incorporated inside the Amundsen-Scott South Pole station [33], no crew time was needed for walking back and forth to the greenhouse. For the 2019 EDEN ISS experiment phase, all these activities were incorporated into the measurements, resulting in a comparatively lower kg CM-h^{-1} value. In addition, the SPFGC produced a high amount of cucumbers (41% of the total fresh edible biomass) [38] compared to the 14.5% produced during the 2019 EDEN ISS experiment phase. As reported by Zabel *et al.* [38], cucumbers had the highest production rate per unit area and time of the plants grown in the MTF in the 2018 experiment phase. This and the higher ratio of cucumbers can also explain the higher production rate of the SPFGC compared to the MTF. No comparable values for the adjusted production rate considering the crew time caused by remote support were found in the literature.

The OOT 2019 worked 12.60 CM-min day^{-1} m^{-2} inside the MTF. Although there are considerable differences in facility design, this value is higher than the values found in the literature for the previously mentioned MDRS mission, with a value of 9 CM-min day^{-1} m^{-2} [20] or the BIOS-3 experiment from December 1972 to June 1973, with a value of 8 CM-min day^{-1} m^{-2} [47, 102]. Only the measurements taken during a HI-SEAS mission in 2014 show a higher value of 31.2 CM-min day^{-1} m^{-2} [23].

Crew Time Development over Time

The analysis of the crew time in this chapter has shown that there is a shift in crew time over time. The crew time for the RST 2019 increased from the beginning of the growth period to when the plants were fully grown in the greenhouse. After that, the crew time needed for remote support decreased due to the fact that the OOT 2019 got more and more familiar with the system and the procedures required to operate the greenhouse, as well as because the number of plants was reduced at the end of the 2019 experiment phase. The crew time development of the OOT 2019 showed similar behavior.

The increasing independence of the OOT 2019 from the RST 2019 over the course of the 2019 experiment phase can also be seen in the fact that the time shares for the nominal support category related to the total RST 2019 crew time (without organizational work for the next mission and off-nominal events) decreased over time and the time shares for the nominal meeting category increased, while the housekeeping category stayed relatively constant.

In addition, the time shares of the total crew time for the RST 2019 (without organizational work for the next mission) related to the overall crew time decreased over the course of the 2019 experiment phase with fluctuations caused by off-nominal events and additional nominal support. Accordingly, the time shares of the total crew time increased for the OOT 2019.

Remote Support Crew Time Categorization

Stromgren *et al.* [41] proposed a methodology for crew time categorization, which could be used for future crew time investigation to allow for a comparison between studies. One important aspect to mention is that the categorization of Stromgren *et al.* [41] did not incorporate crew time values for planetary surface greenhouse tasks since the values were based on tasks onboard the ISS.

In this chapter, a first categorization methodology for crew time with respect to remote support tasks of a planetary surface greenhouse was proposed. This methodology can be used for the analysis and comparison of the remote support crew time measured in planetary surface greenhouse studies as a baseline for the planning/design process for future space missions, in which crew time requirements should be considered as early as possible [45]. This will help to understand which tasks are required and, based on that, to better assess the amount of crew time needed for such missions in order to decrease the deviations of planned crew time from actual crew time discovered in Russell *et al.* [45].

As mentioned previously, using a science category is of great importance for the planning process of future planetary surface greenhouses, although it has not yet been used in this study. Future planetary surface greenhouses will have the purpose to grow food and recycle air or water for the resident habitat crew. These activities are sometimes coupled with science experiments, but not necessarily. Without the science category, the crew time for remote support would be inflated by the crew time for science-related activities, which are not necessarily utilized to operate the greenhouse for the purpose of, for example, food production and air or water recycling. Using science inflated crew time values could result in the decision against greenhouses during the planning of future space missions due to crew time numbers that are too high, which do not reflect reality.

Remote support of the MTF during the past winter seasons has shown that it is not always trivial to attribute the occurred crew time to either the science category or to the nominal support/meeting categories. During a common telephone conference between RST and OOT, several questions were raised by the OOTs. These questions comprised topics attributed to the science category and to the nominal support/meeting categories. However, it would have been difficult to assign crew time demands to the corresponding category subsequent to the meeting.

Potential Enhancements of Future Measurements

The collected measurements may incorporate inaccuracies to some extent. The time period of the 2019 experiment phase was quite long, and the RST 2019 and the OOT 2019 had to record their crew time every day. Due to this, the performance of the crew time recordings may have decreased over the course of the 2019 experiment phase. In addition, participants may have forgotten to record their crew time immediately after performing the tasks and recorded it later based on their memory, which might have influenced the measurements. To increase the accuracy of the crew time measurements, it would be advisable to improve the usability of the measurement procedure. One possibility would be to use an external measurement device or another person to track the crew time of the greenhouse operators (RST and OOT).

Further investigations are needed to increase the database of crew time values for RST and OOT crew time values for planetary surface greenhouses. It would be beneficial to track the crew time for single tasks over the course of several conducted procedures to facilitate the categorization of the crew time values needed for enhanced planning results of future space missions.

In addition, investigations of crew time with respect to the crop nutritional content would contribute to the field of research in a significant way, as the nutritive aspect of plants will be key in future long-duration space mission scenarios [123]. For early mission scenarios, only small greenhouse modules will be operated as integral parts of Moon or Mars habitats still under development. These greenhouse modules will produce crops with a high water content and a short shelf life, such as lettuces, herbs, or cucumbers, as investigated in the EDEN ISS project [138], as supplemental diet to the pre-packed MREs [139]. However, later mission scenarios would likely include additional crops, which would provide increasing fractions of the crew's caloric and nutritional needs. Here, the relations between greenhouse architectures (e.g., lighting, environmental conditions, or nutrient solution composition), crew time, and edible biomass quantity and quality should be investigated further to aid crop selection, system design, and mission planning.

3.5.2 Workload

The common approach of performing the NASA TLX method for every single task separately was not used in this study. This was done due to the fact that the aim was to compare the average overall workload between the four evaluation groups for a typical workday in the MTF and during remote operations in the MCC.

The number of participants in the workload evaluation is rather small, but this is due to the small number of people operating the greenhouse per year.

The goal of the investigations was not to conduct statistical analyses on the workload assessment during a space analog greenhouse study but rather to get a first impression of the tendency of workload characteristics in such an environment since no value for this could be found in the literature.

Comparison of Workload Values

The workload investigations for all groups involved in the operations of the MTF from 2019 to 2020 have indicated that the RST 2019 + 2020 perceived the highest workload, with a value of 67.5, followed by the SMT 2019/2020, with a value of 54.5. The OOT 2019 and OOT 2020 showed similar values of 39.8 and 37.7, respectively.

With the results from Grier [140], it is possible to grade if an overall workload score of the NASA TLX should be considered high or low in comparison to other NASA TLX studies presented in the literature. For this purpose, Grier [140] studied over 1000 overall NASA TLX workload scores, ranging from 6.2 to 88.5, based on over 200 publications. Grier [140] did not consider the performance of the participant. If a workload is perceived as acceptable not only depends on the workload value itself but also depends on the contextual variables such as level of expertise, situation, or task type [140, 141].

Compared to the overall workload score values presented in Grier [140], the value for the OOT 2019 is higher than 30% of the values presented, the value for the OOT 2020 is higher than 25%, the value for the SMT 2019/2020 is higher than 60%, and the value for the RST 2019 + 2020 is higher than 80% of the values presented. It has to be mentioned that the value for the ninth decile is 68.0. A direct comparison with workload scores for planetary surface greenhouses, other analog missions with greenhouses, or plant growth chambers onboard the ISS would be favored, but values for these scenarios were not found in the literature.

A set of contextual factors has influenced the assessment of the workload. These factors are the amount of people operating the greenhouse, type of tasks, expertise of operators, time pressure, environmental conditions, i.e., isolation and harsh conditions in Antarctica, psychological well-being, autonomy in task planning and execution, or type of feedback generated by the task completion. These factors have to be considered in the planning process of operation procedures for future planetary surface greenhouses to minimize the workload of the operation teams (RST and OOT) as much as possible.

Different Preconditions of the On-site Operator Teams in 2019 and 2020

In contrast to the OOT 2019, which started its work in the greenhouse after a couple of months of the greenhouse hibernation phase, the OOT 2020 started its work directly after the SMT 2019/2020 left NM III. In addition, the OOT 2020 conducted a couple of days more of a basic system training prior to the 2020 winter season with hands-on experience on the plants or system handling during the 2019/2020 summer season, which was not possible for the OOT 2019. Nevertheless, no differences in overall workload between the OOT 2019 and OOT 2020 could be determined.

Reasons could be that different amounts of untrained people were dedicated to the on-site operations of the greenhouse during the experiment phases in 2019 and 2020. A higher number of on-site operators in 2020 could result in a flatter individual learning curve regarding the operations in the greenhouse while starting at a higher skill level due to the higher amount of training activities during the 2019/2020 summer season, compared to the OOT 2019 resulting in similar perceived overall workload. Another impact on the overall workload could be the possibility that the difference in the amount of time spent on the basic system training was not enough to make a difference in perceived overall workload of the OOT 2019 and the OOT 2020. One factor to add is that the overall workload of the OOT 2019 was measured at the end of the 2019 experiment phase. On the other hand, the 2020 experiment phase was still running when the workload of the OOT 2020 was measured. Another assumption is that the perceived workload would have changed over the course of the full 2020 experiment phase, for example, if the OOT 2020 became more familiar with the nominal operations or if the greenhouse experienced a significant number of off-nominal events. It also cannot be ruled out that physiological and psychological effects on the OOT 2020 due to the isolated, confined, extreme environment in the Antarctic would have impacted the workload assessment if done at the end of the 2020 full experiment phase. Although the OOT 2019 maintained work reports during the 2019 experiment phase to track their work in the greenhouse, these did not include workload assessments. As such, the workload evaluation was based purely on memories and feelings at the time of the evaluation. This could also alter the results of the overall workload measurement.

Potential Enhancements of Future Measurements

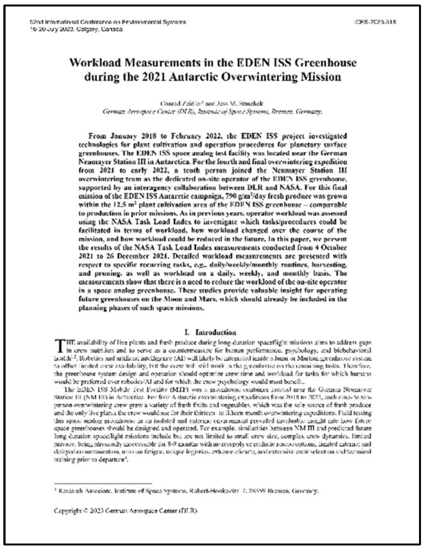
The collected measurements may incorporate inaccuracies to some extent. The fact that the SMT 2019/2020 had already experienced a couple of summer seasons in Antarctica could have impacted the evaluation compared to the OOT 2019 and OOT 2020. The SMT 2019/2020 could have been biased based on the previous experienced summer seasons, rating the experienced workload in 2019/2020 summer season higher (or lower) by comparison. The same applies to the RST 2019 + 2020 since they have already conducted remote support for a couple of years for the OOTs, were already part of the SMTs, and one participant was even part of the 2018 wintering crew. The OOT 2019 and OOT 2020, on the other hand, did not have any reference operating a space analog planetary surface greenhouse, which might have influenced their evaluations as well.

Also, in case of workload measurements, further investigations regarding the perceived workload on task level for remote support and on-site operations for a planetary surface greenhouse are required to better understand which tasks of the specific groups need to be facilitated to improve the outcome and overall performance of a mission. With multiple workload measurements for specific tasks over a longer period, it would also be possible to perform statistical investigations.

It is planned to conduct workload measurements for the various groups involved in the operation process of the EDEN ISS greenhouse every two to four weeks for a typical workday. Additional information about the conducted tasks can be derived from the daily work reports of the operator teams. For some recurrent tasks, task-specific workload measurements will be conducted repeatedly right after task execution to investigate which procedures are more workload intense than others. Moreover, additional crew time measurements are planned to gain more insight into the link between crew time and workload.

Chapter 4

Detailed Workload Investigations



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Workload Measurements in the EDEN ISS Greenhouse during the 2021 Antarctic Overwintering Mission

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From January 2018 to February 2022, the EDEN ISS project investigated technologies for plant cultivation and operation procedures for planetary surface greenhouses. The EDEN ISS space analog test facility was located near the German Neumayer Station III in Antarctica. For the fourth and final overwintering expedition from 2021 to early 2022, a tenth person joined the Neumayer Station III overwintering team as the dedicated on-site operator of the EDEN ISS greenhouse, supported by an interagency collaboration between DLR and NASA. For this final mission of the EDEN ISS Antarctic campaign, 790 g/m²/day fresh produce was grown within the 12.5 m² plant cultivation area of the EDEN ISS greenhouse – comparable to production in prior missions. As in previous years, operator workload was assessed using the NASA Task Load Index to investigate which tasks/procedures could be facilitated in terms of workload, how workload changed over the course of the mission, and how workload could be reduced in the future. In this paper, we present the results of the NASA Task Load Index measurements conducted from 4 October 2021 to 26 December 2021. Detailed workload measurements are presented with respect to specific recurring tasks, e.g., daily/weekly/monthly routines, harvesting, and pruning, as well as workload on a daily, weekly, and monthly basis. The measurements show that there is a need to reduce the workload of the on-site operator in a space analog greenhouse. These studies provide valuable insight for operating future greenhouses on the Moon and Mars, which should already be included in the planning phases of such space missions.

I. Introduction

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Chapter 4 concludes the first part of this thesis and contributes to answering research question **RQ2**. The workload measurement database from Chapter 3 is extended and further detailed with workload data measured in a space analog greenhouse during the EDEN ISS missions. The collected data pertains to the greenhouse on-site operator's recurring tasks and provides daily, weekly, and monthly workload measurements (**C1**).

More extensive measurements revealed the need to reduce the on-site operator's overall workload and identified which NASA TLX dimensions most affect it. In addition, the collected workload data provided insight into which recurring space greenhouse tasks/procedures should be facilitated, automated, or more remotely controlled to reduce the on-site operator workload in future space greenhouses (**C3**). A detailed analysis demonstrated how the workload changed throughout the mission.

The findings presented in this chapter can also be applied to the planning, design, and operations of future greenhouses on the Moon and Mars.

The information presented in this chapter was originally published in *C. Zeidler and J. Bunchek, "Workload measurements in the EDEN ISS greenhouse during the 2021 Antarctic overwintering mission," 52nd International Conference on Environmental Systems, 16-20 July 2023, Calgary, Alberta, Canada, 2023.*

4.1 Introduction

The availability of live plants and fresh produce during long-duration spaceflight missions aims to address gaps in crew nutrition and to serve as a countermeasure for human performance, psychology, and biobehavioral health [142, 143]. Robotics and AI will likely be integrated inside a lunar or Martian greenhouse system to offset limited crew availability, but the crew will still work in the greenhouse on the remaining tasks. Therefore, the greenhouse system design and operations should optimize crew time and workload for tasks for which humans would be preferred over robotics/AI and for which the crew psychology would most benefit.

The EDEN ISS MTF was a greenhouse container located near the German NM III in Antarctica. For four Antarctic wintering expeditions from 2018 to 2022, each nine- to ten-person wintering crew grew a variety of fresh fruits and vegetables, which was the sole source of fresh produce and the only live plants the crew would see for their thirteen- to fifteen-month wintering expeditions. Field testing this space analog greenhouse in an isolated and extreme environment provided invaluable insight into how future space greenhouses should be designed and operated. For example, similarities between NM III and predicted future long-duration spaceflight missions include but are not limited to small crew size, complex crew dynamics, limited privacy, being physically inaccessible for eight to nine months with no resupply or realistic rescue options, limited internet and delayed communication, mission fatigue, unique logistics, extreme climate, and extensive crew selection and technical training prior to departure [144].

Data collection for EDEN ISS has included crew time, workload, and psychology to assess crew interaction with the system and to make predictions for future systems [1, 143]. For the fourth and final EDEN ISS mission from 2021 to early 2022 (referred to as the 2021 mission), a dedicated greenhouse operator from NASA was included in the wintering crew as part of a cooperation between NASA, DLR, and the AWI, the last of which oversees the logistics and operations of NM III. The dedicated on-site operator was tasked with running the MTF for the thirteen-month wintering, and this individual conducted workload measurements from 04.10.2021 to 26.12.2021 using the NASA TLX, with the goal of identifying which tasks and/or procedures should be facilitated with respect to workload.

In this chapter, we present the results of the NASA TLX measurements taken during the final EDEN ISS mission. We report detailed workload measurements on specific recurring tasks, as well as workload on a daily, weekly, and monthly basis. The key contribution of this study recognizes the need to reduce workload in space greenhouses and which dimensions measured in the NASA TLX contribute most to overall workload. Additionally, we highlight which recurring greenhouse tasks should be simplified, remotely supported, or automated for operations in space greenhouses. This information can serve as a valuable baseline for planning future missions to the Moon and Mars, including greenhouse operations.

4.2 EDEN ISS Overview

4.2.1 Mission Background

The 2021 mission included a first austral summer season, the winter isolation phase, and the second summer season (Figure 4.1). During a typical summer season (November to February/March), 50-60 people are at NM III [131]; however, due to the coronavirus pandemic, only 30-40 people were at NM III each summer of the 2021 mission. Summer guests conduct scientific work or on-site maintenance of technical systems and facilities. In contrast, only 9-10 people stay at NM III during the winter isolation phase (February/March to November).

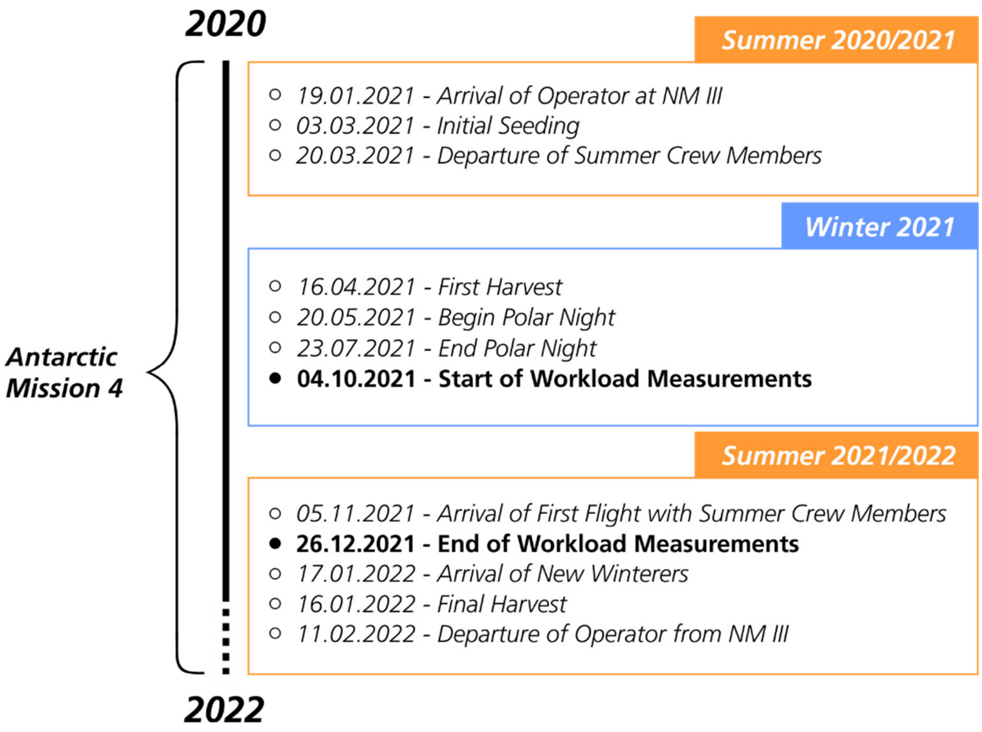

Figure 4.1: Overview of the fourth and final mission of the EDEN ISS Antarctic campaign. Open bullet points represent specific points in time, and solid bullet points represent start and end points of experimentation. NM III = Neumayer Station III.

The 2021 mission started with the arrival of the operator and an experienced DLR summer crew member on 19.01.2021 at NM III. Initial crop seeding for the mission started inside the MTF on 03.03.2021, nearly three weeks before the DLR summer crew member left NM III. The isolation period for the winterers at NM III began on 20.03.2021, and the first harvest was conducted on Mizuna mustard greens on 16.04.2021. Workload measurements were taken from 04.10.2021 to 26.12.2021. The isolation period ended on 05.11.2021 with the arrival of the first summer scientists and technicians. This final mission of the EDEN ISS Antarctic campaign formally ended with the last harvest on 16.01.2022, and the operator continued work in the MTF until departing NM III on 11.02.2022. These final tasks included cleaning, draining system lines, disconnecting components, and putting the MTF into hibernation mode.

4.2.2 Cultivated Crops and Biomass Output

During the 2021 mission, approximately 316 kg edible fresh biomass was grown within the 12.5 m^2 cultivation area of the MTF (Table 4.1). In total, 37 different cultivars were grown throughout the 2021 mission for research and crew consumption, with consideration for crops that had not been previously tested in EDEN ISS and also for crops that had been grown in spaceflight (Table 4.2). Crops were further selected based on the wintering crew's specific taste preferences and interests.

Table 4.1: Monthly harvested fresh edible biomass of cultivated crops during the 2021 mission.

Month	**2021**									**2022**	**Total**
	Apr.	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Jan.**	
Edible fresh mass per month [kg]	22.5	37.2	32.3	16.4	23.2	28.8	23.0	54.6	50.9	26.3	**315.2**

Table 4.2: Crops cultivated in EDEN ISS during the 2021 mission. Indications are included for crops new to EDEN ISS (a) and for crops that have been grown in crop production systems in spaceflight (b).

Plant Group	Type	Cultivar
Lettuces	Frisée	*Expertise RZ*
	Romaine [b]	*Dragoon* [b], *Outredgeous* [b]
	Green leaf [b]	*Waldmann's Green* [b]
	Batavia	*Othilie RZ* [a]
Mustards	Mustard greens [b]	*Red Giant, Amara* [b], *Frizzy Lizzy, Mizuna* [b]
	Pak choi [b]	*Rosie*
	Kale [b]	*Nero Di Toscano* [b]
	Watercress	-
	Arugula	-
	Broccoli greens [a]	-
	Cauliflower greens [a]	-
Other leafy greens	Spinach	*Golden Eye* [a]
	Swiss chard	*Bright Lights*
Herbs	Basil	*Dolly Genovese*
	Chives	*Purly*
	Parsley	*Laura*
	Oregano	*Greek*
	Rosemary	-
	Spearmint	-
	Thyme	-
Fruiting crops	Tomato [b]	*Amoroso, Joy Red* [a], *PAT orange, Red Robin* [b]
	Cucumber	*Picowell RZ*
	Pepper [b]	*Chimayo* [a], *Española* [a,b], *Mimi Red* [a], *Red Skin* [a]
	Beans [a]	-
	Peas [a]	-
Stem crops	Radish [b]	*Raxe*
	Kohlrabi	*Korist*

4.2.3 Typical Workday in MTF

The operator worked nearly every day of the 2021 mission, including weekends and holidays, in the greenhouse. Most of the tasks were conducted in the MTF, but others, such as nutrient stock solution preparation, plant tissue processing, and emails/office work, were completed inside NM III. Each day's workload varied and was affected not only by the plants and tasks but also by the weather and blizzards, station obligations within NM III, and exchanging help with other crew members. While other members of the wintering crew contributed help to EDEN ISS throughout the 2021 mission, the operator was the sole crew member to visit and work inside the greenhouse nearly every day. Thus, this chapter focuses only on the crew time and tasks conducted by the operator inside the MTF. Examples of typical workdays during the surveyed period are shown in Table 4.3.

Table 4.3: Examples of operator crew time (CT) and nominal tasks inside the Mobile Test Facility.

Day A – 31.10.2021		**Day B – 27.11.2021**		**Day C – 13.12.2021**	
Task	**Total Duration [h]**	**Task**	**Total Duration [h]**	**Task**	**Total Duration [h]**
Harvesting (lettuce, mustards, beans)	2.8	Harvesting (tomatoes)	2.3	Harvesting (peppers)	3.9
Plant data collection	1.0	Plant data collection	0.7	Plant data collection	1.0
Daily checks; Pruning/Trellising	0.2	Daily checks; Pruning/Trellising	1.7	Daily checks; Pruning/Trellising	0.5
Maintenance/Repairs	0.2	Maintenance/Repairs	0.3	Maintenance/Repairs	0.2
Daily Total CT	**4.2**	**Daily Total CT**	**5.0**	**Daily Total CT**	**5.6**

The operator received remote support throughout the 2021 mission from teams at DLR's Institute of Space Systems in Bremen, Germany, and NASA's Kennedy Space Center in Florida, USA. Communication via text messages, telephone, or emails was utilized, depending on the topic and urgency. Topics of the regularly scheduled calls with the RST included data collection, scheduling and logistics planning, ongoing system repairs or challenges, and public outreach. Due to limited communication and internet capabilities, members of the RST could contact additional experts or product manufacturers on behalf of the operator to address specific questions.

A typical workday started in the station and included office work and any preparations needed to complete that day's tasks in the MTF. Preparations could include freshwater or nutrient stock solution preparation, planning for harvests, repairing components from the greenhouse in the station's workshops, and cleaning components brought to NM III from the greenhouse. The operator then walked the 400 m distance from NM III to the MTF and completed that day's activities. Some activities, like pollinating tomatoes and peppers, took 1-2 min and were conducted daily. Other routine activities were completed weekly, monthly, or seasonally, such as exchanging filters and ozone cells, additional system checks, and cleaning. More intense tasks, like troubleshooting an electrical issue, cleaning pumps, and harvesting large plants that included additional data collection and sampling, could require a whole day, if not multiple days, to be accomplished. These larger tasks, however, typically occurred less frequently at different points in the system and on a rotation of crops. After completing the tasks in the MTF, the operator would return to NM III and complete any remaining tasks for the day, which could include more office work, data organization, and processing and storing plant tissue samples, nutrient solution samples, or surface swabs intended for microbiology/food safety analyses.

4.3 Workload Recordings within EDEN ISS

4.3.1 Participant

The operator measured her workload during the 2021 mission. The operator had botanical expertise, experience operating plant growth facilities in conventional agriculture and spaceflight systems, and technical and physical work skillsets. However, prior to arrival at NM III, the operator was not yet familiar with the MTF systems beyond journal publications, technical documents, and manuals. Thus, the DLR summer crew member, who had worked on the MTF during the design/construction phase and in Antarctica during previous summer seasons, trained the operator on-site during the summer from mid-January to mid-March 2021. This was coupled with the annual cleaning, maintenance, and recalibrations of all systems and components in the MTF. Finally, the operator was trained on how and where to conduct EDEN ISS related tasks inside NM III.

4.3.2 Measurement Collection

The NASA TLX questionnaire was used as the multidimensional assessment method to measure workload characteristics during the operations of the MTF. This questionnaire is widely used in various application scenarios, such as assessing factors relevant to crew success and performance (e.g., stress, fatigue, or crew size) [55]. The NASA TLX can be used to evaluate the workload of one or more individuals based on six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration [53, 54].

When using the NASA TLX, the participant retrospectively assesses a task for the six dimensions, and each dimension is measured on a 20-point bipolar scale with scores ranging from 0 to 100 in increments of five. In addition to the raw ratings, a pairwise comparison is made to calculate weights. These weights describe which of the six dimensions contributes most to workload for the tasks performed. Adjusted ratings, which can range from 0 to 500, are calculated by multiplying the dimension-specific raw ratings by the related weights. All adjusted ratings are then processed to form the overall score workload values between 0 and 100. [53, 56, 136]

Workload was measured during the 2021 mission between 04.10.2021 and 26.12.2021 (Table 4.4). For these twelve weeks, workload measurements were taken for specific recurring tasks such as procedures (e.g., changing tanks, repairing broken pumps), daily/weekly/monthly routines (checklists), harvesting, checking plant health, checking system status, and pruning. Multiple measurements were taken for most specific tasks. Workload was also measured for a full set of tasks for one day, one week, and one month. The operator worked approximately 5 h day^{-1} in the MTF during this period. The NASA TLX was completed by the operator on the days listed in Table 4.4 using paper questionnaires.

Table 4.4: Timeline for workload (WL) measurements on a monthly, weekly, and daily basis and for specific recurring tasks with measurement times. Furthermore, measurement times of NASA TLX weights are listed.

Week		**NASA TLX Measurements**					
		Weights		**Monthly WL**	**Weekly WL**	**Daily WL**	**WL for Specific Tasks**
1	**04.10. - 10.10.2021**	**A**	04.10.2021		10.10.2021		
2	**11.10. - 17.10.2021**				17.10.2021	each day of this week	tasks in this week
3	**18.10. - 24.10.2021**	**B**	18.10.2021		24.10.2021	each day of this week	tasks in this week
4	**25.10. - 31.10.2021**				31.10.2021		
5	**01.11. - 07.11.2021**	**C**	01.11.2021	01.11.2021	07.11.2021		
6	**08.11. - 14.11.2021**				14.11.2021	each day of this week	tasks in this week
7	**15.11. - 21.11.2021**	**D**	15.11.2021		21.11.2021	each day of this week	tasks in this week
8	**22.11. - 28.11.2021**				28.11.2021		
9	**29.11. - 05.12.2021**	**E**	29.11.2021	30.11.2021	05.12.2021		
10	**06.12. - 12.12.021**				12.12.2021	each day of this week	tasks in this week
11	**13.12. - 19.12.2021**	**F**	13.12.2021		19.12.2021	each day of this week	tasks in this week
12	**20.12. - 26.12.2021**			26.12.2021	26.12.2021		

4.4 Results

4.4.1 Workload on a Monthly Basis

The operator completed monthly NASA TLX measurements at the end of October, November, and December, which encompassed total workload performed inside the MTF across each month. The adjusted ratings for each of the six dimensions and the overall workload score are visualized in Table 4.5 and Figure 4.2. The mean of the three months and SEM are included.

Table 4.5: NASA TLX adjusted ratings of dimensions and overall workload scores measured by the operator for a full set of tasks inside the Mobile Test Facility on a monthly basis, as well as the mean and standard error of the mean (SEM) of the months (n=3).

	Adjusted Rating				
	Months (n=3)		**October (n=1)**	**November (n=1)**	**December (n=1)**
	Mean	**SEM**			
Mental Demand	178.33	23.51	160.00	150.00	225.00
Physical Demand	170.00	16.07	175.00	195.00	140.00
Temporal Demand	352.50	64.08	225.00	427.50	405.00
Performance	70.00	11.55	50.00	70.00	90.00
Effort	90.83	7.95	97.50	75.00	100.00
Frustration	20.00	20.00	60.00	0	0
Overall Score	**58.78**	**3.89**	**51.17**	**61.17**	**64.00**

Overall Workload Score

The overall workload scores of the operator show slightly increasing values from October (51.2) through November (61.2) to December (64.0) but are in a similar range (Figure 4.2). The mean of all three months is 58.8 (SEM=3.89).

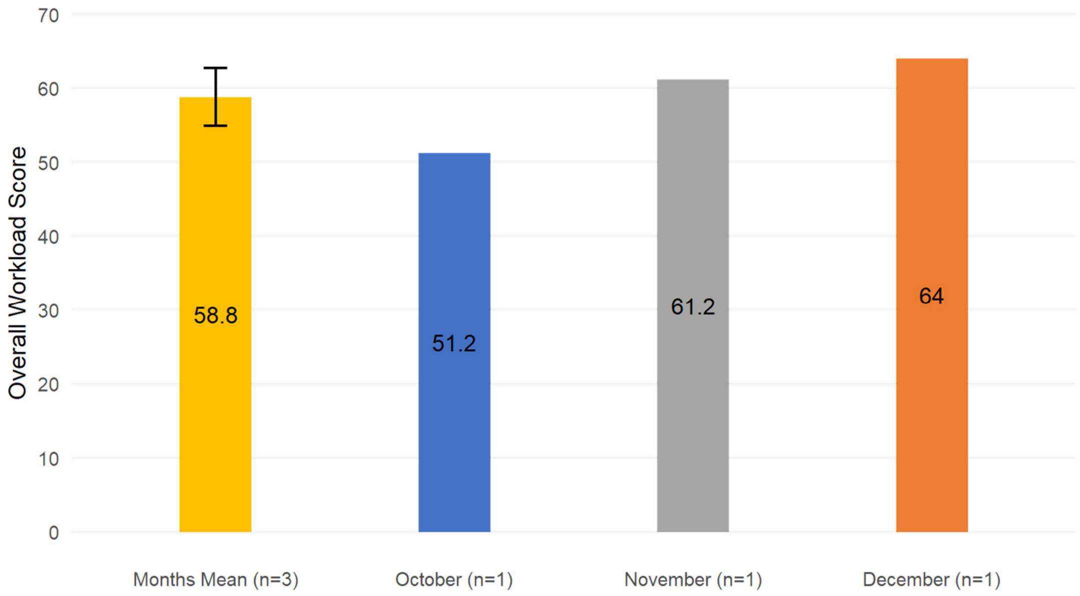

Figure 4.2: NASA TLX overall workload scores measured by the operator for a full set of tasks inside the Mobile Test Facility on a monthly basis across October to December, as well as the mean and standard error of the mean (SEM) of the months (n=3).

Adjusted Ratings

The adjusted ratings (Figure 4.3 and Table 4.5) were measured for a full set of tasks inside the MTF and build the baseline for the overall workload scores. On a monthly basis, temporal demand was rated the highest among the six dimensions, with an average value of 352.5 (SEM=64.08).

The specific values for November and December are in a similar range and show the overall highest values at 427.5 and 405.0, respectively. The value for October is half as high at a value of 225.0.

This can be explained by the fact that the time pressure experienced by the operator toward the end of the 2021 mission was higher compared to October when additional tasks pertained to preparing for the upcoming summer season and concluding the winter isolation phase.

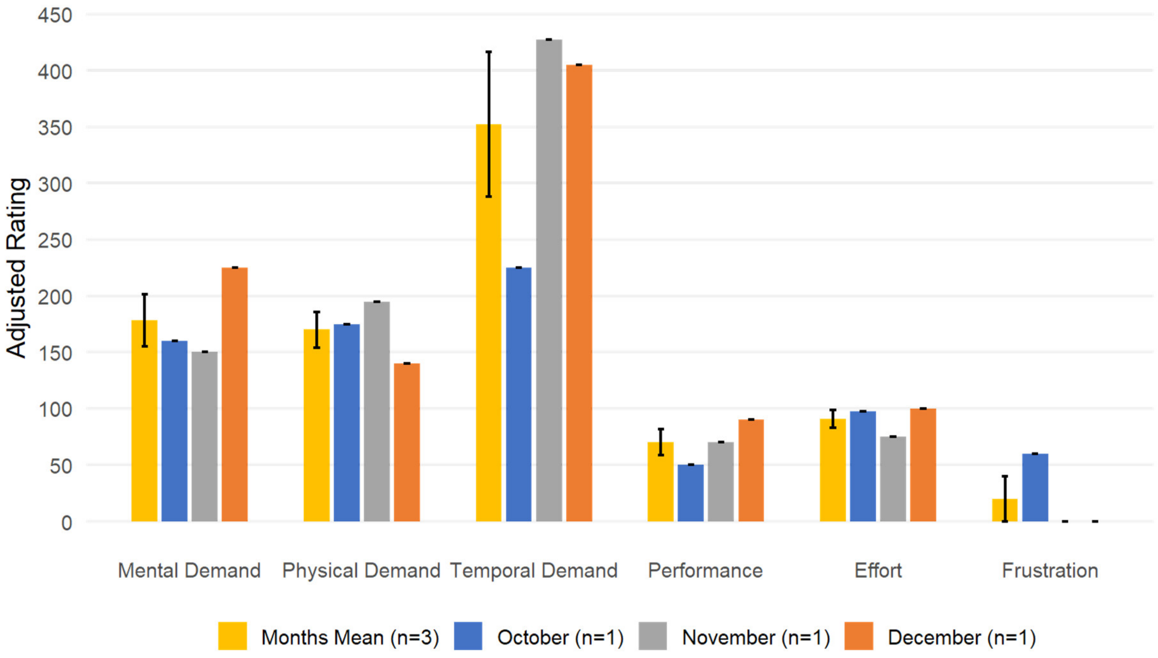

Figure 4.3: NASA TLX adjusted ratings of dimensions measured by the operator for a full set of tasks inside the Mobile Test Facility on a monthly basis across October to December, as well as the mean and standard error of the mean (SEM) of the months (n=3).

Mental demand and physical demand were reported in a similar range, representing the second highest values with averages of 178.3 (SEM=23.51) and 170.0 (SEM=16.07), respectively. The December value for mental demand shows an upward outlier value of 225.0, compared to October with a value of 160.0 and November with a value of 150.0. The values for physical demand are 175.0 for October, 195.0 for November, and 140.0 for December, with no noteworthy outliers.

The higher mental demand value in December can be explained by the fact that the operator experienced several system failures during the month, which had to be promptly fixed.

The values for performance and effort are also in a similar range with average values of 70.0 (SEM=11.55) and 90.8 (SEM=7.95), respectively, although only half as high as compared to mental demand and physical demand. Performance has the lowest value in October with a value of 50.0, followed by November with a value of 70.0, and the highest value in December at 90.0. This shows a slightly increasing trend over time for performance. The lowest value for effort is shown in November with a value of 75.0, followed by similar values in October with 97.5 and December with 100.0.

Performance became more valued over time as the operator completed end-of-mission tasks such as last harvests and cleanings, as well as a joint agency press conference hosted by NASA and DLR. As the 2021 mission neared the end, the operator also became increasingly aware of the decreasing time to complete all remaining tasks prior to departure, which contributed to higher performance and effort values in December. Effort in November was lower, as the operator completed primarily nominal tasks.

The lowest adjusted ratings among the six dimensions are for frustration, with an average value of 20.0 (SEM=20.00). The values for November and December are zero and thus the lowest measured. The value for October shows an outlier with a value of 60.0.

The reason for this outlier could be the fact that October was still during the winter isolation phase, which still included cold temperatures and increasing workload at the station to prepare for the summer season. Thus, stress to complete tasks prior to the arrival of summer guests contributed to operator frustration, especially in the case of unanticipated tasks such as repairs. However, at this point in the 2021 mission, the operator was so familiar with the MTF that tasks, especially repairs, could be completed without assistance from the RST.

4.4.2 Workload on a Weekly Basis

The operator completed NASA TLX measurements each week during the sample period. Table 4.6 shows the adjusted ratings of dimensions and overall workload scores of the operator for a full set of tasks inside the MTF as mean for all weekly measurements and mean grouped across each of the three months of the sample period.

Table 4.6: NASA TLX adjusted ratings of dimensions and overall workload scores measured by the operator on a weekly basis for a full set of tasks inside the Mobile Test Facility, with data grouped by month, as well as the mean and standard error of the mean (SEM) for all weekly measurements (n=12).

	Adjusted Rating							
	Weeks (n=12)		**Weeks October (n=4)**		**Weeks November (n=4)**		**Weeks December (n=4)**	
	Mean	**SEM**	**Mean**	**SEM**	**Mean**	**SEM**	**Mean**	**SEM**
Mental Demand	224.58	20.31	223.75	52.69	183.75	15.46	266.25	19.72
Physical Demand	163.33	21.05	130.00	34.94	212.50	48.54	147.50	6.29
Temporal Demand	320.42	40.21	198.75	46.79	355.00	74.25	407.50	47.15
Performance	77.92	16.98	80.00	46.90	68.75	26.49	85.00	15.00
Effort	85.00	14.87	82.50	48.02	77.50	7.77	95.00	3.54
Frustration	28.33	16.86	85.00	39.00	0	0	0	0
Overall Score	**59.97**	**3.49**	**53.33**	**6.18**	**59.83**	**6.86**	**66.75**	**4.37**

Additionally, the NASA TLX adjusted ratings of dimensions and overall workload scores of the operator for a full set of tasks inside the MTF are provided in Table 4.7, with data presented for each of the twelve weeks.

Table 4.7: NASA TLX adjusted ratings of dimensions and overall workload scores measured by the operator on a weekly basis for a full set of tasks inside the Mobile Test Facility for the twelve weeks across October to December. For all weeks, n=1.

	Adjusted Rating											
	Week 1	**Week 2**	**Week 3**	**Week 4**	**Week 5**	**Week 6**	**Week 7**	**Week 8**	**Week 9**	**Week 10**	**Week 11**	**Week 12**
Mental Demand	135	210	175	375	225	180	180	150	300	300	225	240
Physical Demand	225	75	140	80	170	100	320	260	160	130	150	150
Temporal Demand	255	60	225	255	380	140	475	425	500	450	280	400
Performance	0	0	180	140	100	125	40	10	100	40	100	100
Effort	150	180	0	0	95	60	70	85	100	95	85	100
Frustration	195	15	80	50	0	0	0	0	0	0	0	0
Overall Score	**64.00**	**36.00**	**53.33**	**60.00**	**64.67**	**40.33**	**72.33**	**62.00**	**77.33**	**67.67**	**56.00**	**66.00**

Overall Workload Score

The overall workload scores for a full set of tasks inside the MTF for the twelve weeks of October through December have minimum values of 36.0 for week 2 and 40.3 for week 6, with maximum values in week 7 and week 9 with values of 72.3 and 77.3, respectively (Table 4.7). Overall, Table 4.7 the data shows a slight upward trend in overall workload measurements.

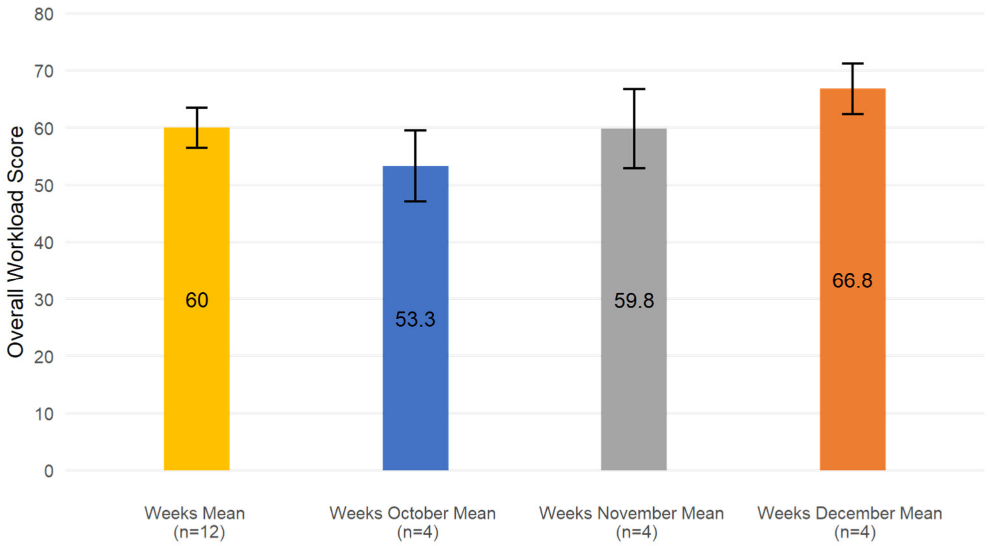

Figure 4.4: NASA TLX overall workload scores including standard error of the mean (SEM) measured by the operator on a weekly basis for a full set of tasks inside the Mobile Test Facility as mean for the weeks across October to December, as well as the mean and standard error of the mean for all weekly measurements (n=12).

Figure 4.4 shows the overall workload scores of the operator measured for a full set of tasks inside the MTF as means for the weeks of October through December. The results of the workload measurements on a weekly basis show almost the same values as mean for a full month as the monthly measurements (Figure 4.2). The values slightly increase from October with 53.3 (SEM=6.18) through November with 59.8 (SEM=6.86) to December with 66.8 (SEM=4.37), but are in a similar range. The mean of all three months is 60.0 (SEM=3.49).

Adjusted Ratings

The adjusted ratings (Figure 4.5 and Table 4.6) were measured for a full set of tasks inside the MTF and build the baseline for the overall workload scores.

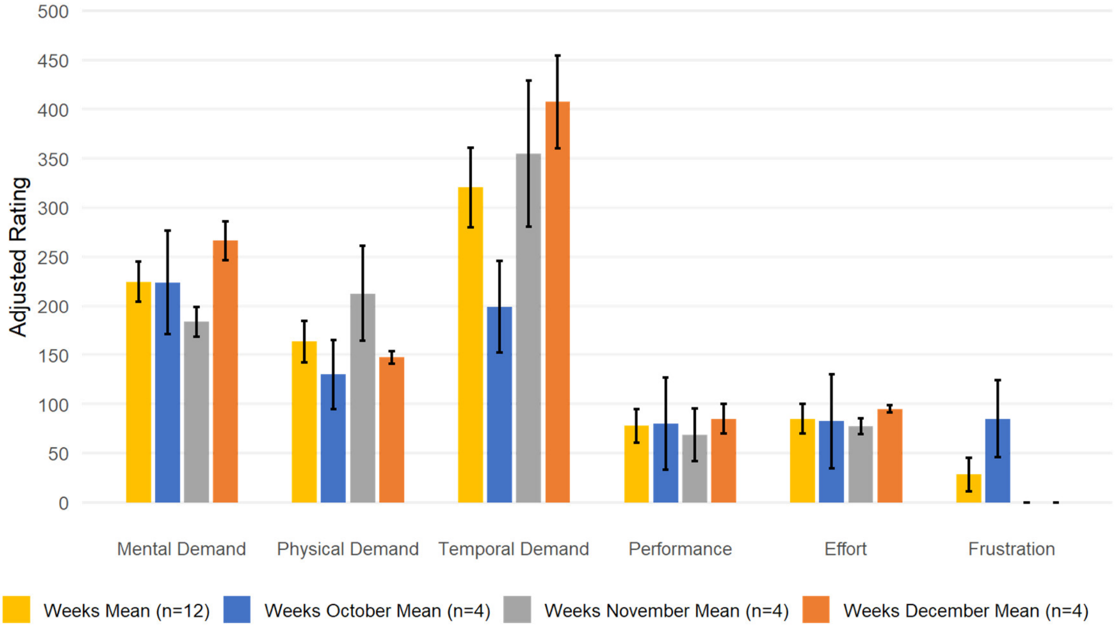

Figure 4.5: NASA TLX adjusted ratings of dimensions including standard error of the mean (SEM) measured by the operator on a weekly basis for a full set of tasks inside the Mobile Test Facility as mean for the weeks across October to December, as well as the mean and standard error of the mean for all weekly measurements (n=12).

The mean adjusted ratings based on weekly measurements show similar values compared to the values measured monthly. The values are slightly lower for mental demand measured monthly (Figure 4.3) than measured weekly (Figure 4.5). The values for physical demand are almost identical except for the value for October, which is lower when measured weekly with a value of 130.0 (SEM=34.94) compared to 175.0 when measured monthly. The values for temporal demand are almost identical in both analyses; only the values for November are lower when measured on a weekly basis (355.0; SEM=74.25) than on a monthly basis (427.5). Performance values are also almost identical in both analyses; only the value for October increases from 50.0 to 80.0 (SEM=46.90) when measured on a monthly and weekly basis, respectively. Further, the values for effort and frustration are almost identical in both analyses, with no outliers.

Adjusted ratings measured on a weekly basis (Figure 4.6 and Table 4.7) also show the same rankings of the six dimensions compared to the adjusted ratings measured on a monthly basis (Figure 4.3). Temporal demand shows the highest values among the six dimensions. Mental demand and physical demand show values in a similar range, representing the second highest values with slightly higher values for mental demand. Performance and effort have the third highest values and are also in a similar range. The lowest adjusted ratings among the six dimensions are for frustration.

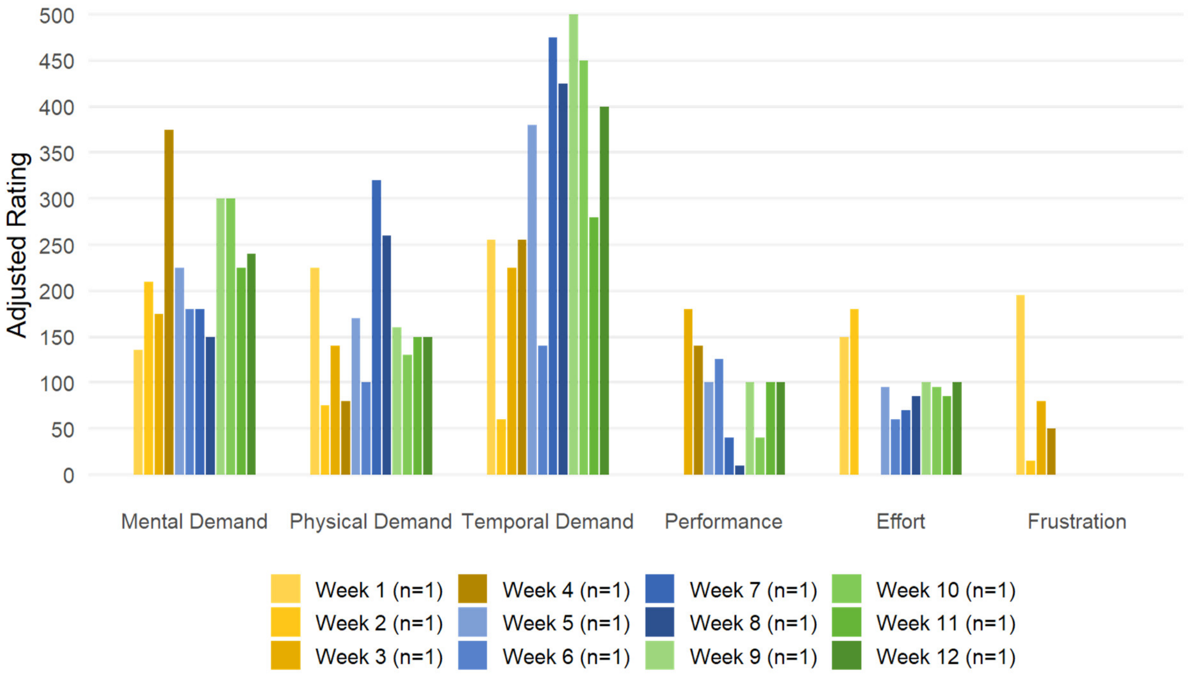

Figure 4.6: NASA TLX adjusted ratings of dimensions measured by the operator on a weekly basis for a full set of tasks inside the Mobile Test Facility for the weeks of October (yellowish bars), November (blueish bars), and December (greenish bars).

The more detailed resolution of the adjusted ratings (Figure 4.6) shows that the mental demand is slightly increasing from the first to the twelfth week, with the highest mental demand in the weeks of December. This can be attributed mostly to increasing operator fatigue and a consistently high and rigorous workload to complete toward the end of the 2021 mission. The highest value is an outlier measured for the fourth week with a value of 375.0. Also, for physical demand, a slight increase can be seen during the twelve weeks. The highest values, which present outliers, are measured in week 1 (225.0), week 7 (320.0), and week 8 (260.0). For temporal demand, a high increase in the adjusted ratings can be seen in Figure 4.6, with the lowest value of 60.0 in week 2 and the highest value of 500.0 in week 9. Week 2 and week 6 show values with relatively low outliers. Performance shows values in the range of 100.0 over the course of the twelve weeks. Values of zero can be seen for the first two weeks, followed by the highest values for week 3 (180.0) and week 4 (140.0). In week 8, another really low value of 10.0 was measured. Effort shows values in the range of 90.0 for the last eight weeks. Week 2 has the highest value of 180.0, followed by week 1 with a value of 150.0. These two weeks are followed by two weeks with an adjusted value of zero. Frustration shows the lowest values of all six dimensions, with a value of zero for the last eight weeks. Adjusted ratings with the highest value in week 1 of 195.0 and lowest value in week 2 of 15.0 were measured during the first four weeks.

4.4.3 Workload on a Daily Basis

The operator also completed NASA TLX measurements for a full set of tasks inside the MTF each day during six selected weeks. The weeks during which daily measurements were collected were grouped into three sets of two weeks, with two weeks between each set in which no daily measurements were taken. The adjusted ratings of dimensions and overall workload scores on a daily basis, as mean for all daily measurements and as grouped by week, are presented in Table 4.8 and Table 4.9. Only the mean values for the daily measurements were analyzed in an effort to smooth variations in the data from one day to the next. These variations are attributed to factors beyond the focus of this study, such as weather conditions, not MTF related commitments or the mental being of the operator.

Table 4.8: NASA TLX adjusted ratings of dimensions and overall workload scores measured by the operator on a daily basis for a full set of tasks inside the Mobile Test Facility as mean for all daily measurements, including standard error of the mean (SEM) (n=40). To match the format used in this thesis, Table 8 from Zeidler and Bunchek [3] has been split into Table 4.8 and Table 4.9.

	Adjusted Rating	
	Days (n=40)	
	Mean	**SEM**
Mental Demand	169.02	12.48
Physical Demand	122.20	12.66
Temporal Demand	232.32	19.01
Performance	81.10	10.45
Effort	72.80	10.83
Frustration	13.66	3.96
Overall Score	**47.23**	**2.47**

Table 4.9: NASA TLX adjusted ratings of dimensions and overall workload scores measured by the operator on a daily basis for a full set of tasks inside the Mobile Test Facility as mean for six weeks across October to December, including standard error of the mean (SEM). To match the format used in this thesis, Table 8 from Zeidler and Bunchek [3] has been split into Table 4.8 and Table 4.9.

	Adjusted Rating											
	Week 2 (n=6)		**Week 3 (n=7)**		**Week 6 (n=6)**		**Week 7 (n=7)**		**Week 10 (n=7)**		**Week 11 (n=7)**	
	Mean	**SEM**	**Mean**	**SEM**	**Mean**	**SEM**	**Mean**	**SEM**	**Mean**	**SEM**	**Mean**	**SEM**
Mental Demand	207.50	11.24	192.86	44.56	137.50	29.09	154.29	27.53	180.00	27.77	167.14	26.27
Physical Demand	190.00	31.38	98.57	19.57	71.67	20.23	168.57	42.95	104.29	26.53	120.00	21.27
Temporal Demand	185.00	15.33	175.71	30.48	236.67	52.26	296.43	44.13	292.86	59.69	234.29	45.92
Performance	0	0	105.71	22.56	145.83	28.44	62.86	8.37	60.00	12.34	121.43	27.51
Effort	217.50	11.46	0	0	50.00	10.57	53.57	9.62	71.43	9.24	72.14	9.63
Frustration	52.50	11.46	35.00	10.12	0	0	0	0	0	0	0	0
Overall Score	**56.83**	**3.51**	**40.52**	**5.97**	**42.78**	**6.30**	**49.05**	**6.67**	**47.24**	**6.58**	**47.67**	**6.51**

Overall Workload Score

The results of the workload measurements on a daily basis show smaller mean overall workload scores (Table 4.8 and Table 4.9) compared to measurements taken on a monthly (Table 4.5) and weekly basis (Table 4.6). The mean overall workload score for week 2 has the highest value of the daily measurements with 56.8 (SEM=3.51). This value is comparable to the weekly (59.4; SEM=3.48) and monthly means (58.8; SEM=3.89). The mean overall workload scores for the other weeks in Table 4.9 are at a similar level and range between 40.5 (SEM=5.97) for week 3 and 49.1 (SEM=6.67) for week 7. The values on a daily basis also show smaller overall workload values compared to the weekly measured values of Table 4.7, with the values for week 6 being similar, while the value for week 2 is higher.

Adjusted Ratings

The six dimensions of the mean adjusted ratings measured on a daily basis (Table 4.8 and Table 4.9) show the same ranking compared to the adjusted ratings measured on a weekly (Figure 4.5) and monthly basis (Figure 4.3). Temporal demand ranks first, mental demand and physical demand rank second with slightly higher values for mental demand, performance and effort rank third, and frustration ranks fourth. Almost all adjusted ratings as mean of all 40 days (Table 4.8) show smaller values compared to the adjusted ratings as mean of all twelve weeks (Figure 4.5). Only for performance are the values slightly higher for the mean of all 40 days (81.1; SEM=10.45) compared to mean of all twelve weeks (77.9; SEM=16.98).

Further, the specific weekly values of the mean adjusted ratings measured on a daily basis (Table 4.9) show lower values than those measured on a weekly basis (Table 4.7 and Figure 4.6). Higher values were reported only for performance at weeks 6, 7, 10, and 11, as well as for mental demand at week 3 and temporal demand at week 6. In addition, the values for physical demand, temporal demand, effort, and frustration are higher in week 2. Differences can reach values of up to 179 such as for the values of temporal demand for week 7.

4.4.4 Workload for Specific Recurring Tasks

The NASA TLX overall workload scores, including SEM, of the operator for specific tasks inside the MTF are displayed in Table 4.10. The specific tasks are sorted by the four categories proposed by Zabel *et al.* [48]: Crop Cultivation, Maintenance, Repair, and Science. All tasks that could not be assigned to one of these four categories are assigned to a fifth one: Miscellaneous. The n-value in the task column indicates how many measurements were taken for that specific task.

Crop Cultivation includes harvesting, pruning, pollinating, sowing, and transplanting crops. Harvesting is subcategorized by crop cultivar. The highest overall workload score for Crop Cultivation was Dolly Genovese basil harvest (59.3), while the lowest value was measured for Red Skin pepper harvest (19.0). The total mean of overall workload scores in this category is 32.1 (SEM=2.64).

Maintenance is subdivided into tasks such as daily checks, cleaning, adding hydrogen peroxide (H_2O_2) to the nutrient delivery tanks to prevent microbial growth, shoveling and plowing snow outside the MTF, CO_2 bottle exchange, fresh water tank filling, plant checks, nutrient solution preparation, light programming, acid preparation and exchange, and waste water processing. The highest overall workload score for Maintenance was measured for nutrient solution preparation (57.3), while the lowest value was measured for acid preparation and exchange (12.3; SEM=0.33). The total mean of overall workload scores in this category is 35.2 (SEM=2.83), which is in the same range as for Crop Cultivation.

Repairs include activities for mitigating anomalies, such as pump failures. This category has an overall workload score of 42.3 (SEM=12.00), which is slightly higher than the values for Crop Cultivation and Maintenance.

For Science, tasks such as weighing samples, microbial sampling inside the MTF, scientific data review, and work on a prototype hydroponic system from NASA called the Passive Porous Tube Nutrient Delivery System (PPTNDS) were investigated. The highest overall workload score was measured for microbial sampling (52.9; SEM=5.87), while the lowest value (32.5; SEM=3.94) was measured for weighing. The total mean of overall workload scores in this category is 41.7 (SEM=2.69), which is similar to Repair.

Table 4.10: NASA TLX overall workload scores, including standard error of the mean (SEM) of the operator for specific tasks inside the Mobile Test Facility. PPTNDS = Passive Porous Tube Nutrient Delivery System.

Category	Task		Mean Overall Score	SEM	Total Mean Overall Score
Crop Cultivation	Harvesting	Red Giant (n=1)	51.00	-	**32.10 (SEM=2.64)**
		Watercress (n=2)	31.00	5.17	
		Red Robin (n=2)	33.00	1.33	
		Fallen fruits (n=2)	26.83	3.50	
		Korist (n=1)	26.67	-	
		Rosie (n=1)	53.67	-	
		Picowell RZ (n=2)	32.67	4.00	
		Dolly Genovese (n=1)	59.33	-	
		Chimayo (n=1)	43.33	-	
		Española (n=1)	38.33	-	
		Red Skin (n=1)	19.00	-	
	Pruning (n=3)		29.78	6.16	
	Pollinating (n=8)		22.75	5.18	
	Sowing (n=1)		48.00	-	
	Transplanting (n=1)		41.00	-	
Maintenance	Daily check (n=9)		31.30	5.04	**35.23 (SEM=2.83)**
	Cleaning (n=13)		45.36	3.43	
	Adding H_2O_2 (n=7)		18.95	6.57	
	MTF shoveling (n=2)		48.83	14.83	
	CO_2 bottle exchange (n=1)		29.00	-	
	Fresh water tank filling (n=2)		48.83	7.83	
	Plant checks: beans (n=1)		54.00	-	
	Nutrient solution preparation (n=1)		57.33	-	
	Light programming (n=1)		16.00	-	
	Acid preparation & exchange (n=2)		12.33	0.33	
	Waste water processing (n=1)		28.67	-	
Repair	Repairs (n=2)		42.33	12.00	**42.33 (SEM=12.0)**
Science	Weighing (n=5)		32.47	3.94	**41.77 (SEM=2.69)**
	Microbial sampling (n=5)		52.93	5.87	
	Data review (n=3)		46.11	6.01	
	PPTNDS work (n=14)		40.17	3.88	
Miscellaneous	Office work (n=3)		38.56	4.26	**42.84 (SEM=4.20)**
	Return freight organization (n=6)		52.22	6.17	
	Photography (n=2)		19.83	9.17	
	EDEN tour (n=2)		33.00	4.67	
	Outreach (n=2)		54.00	8.67	

Miscellaneous consists of tasks such as office work inside NM III, organizing return freight to DLR, photographing plants and systems, giving tours inside the MTF, and outreach activities. The highest value (54.0; SEM=8.67) was measured for outreach and the lowest value (19.8; SEM=9.17) for photography. The total mean of overall workload scores in this category (42.8; SEM=4.20) is also in the same range as those in Repair and Science.

4.5 Discussion and Conclusion

To ensure a more objective evaluation of workload for operations in a space analog greenhouse, it would have been advantageous to have multiple participants completing workload measurements using the NASA TLX. This was not possible because only one operator was in Antarctica during the 2021 mission, so the results reported here could be subjectively biased by individual preferences, moods, or experiences. An attempt was made to be as objective as possible by measuring over a period of three months.

While the EDEN ISS Antarctic campaign was similar in many aspects to future missions to the Moon or Mars [18, 131], these mission scenarios will still differ in some aspects.

First, since the perceived workload depends on the specific mission scenario and the associated system architecture, the workload characteristics may be different for lunar surface greenhouses compared to the measurements in this chapter. For example, a lunar greenhouse will most likely be directly connected to a habitat and have various interfaces with the habitat (e.g., water, energy, or waste). [2] This will make transportation of scientific equipment, spare parts, fresh water, or waste water, which were necessary for EDEN ISS, obsolete or at least greatly reduced. This will have implications on various dimensions of the workload, such as physical demand, time demand, and frustration.

Further, there will not be a summer season in future planetary surface missions during which the new astronaut crew will be trained. However, this remains comparable to the ISS, where there is an overlapping familiarization period for changing crews, and is also conceivable for future planetary surface missions. [2]

Additionally, compared to the two-second one-way telephone delay and minimal internet connection between NM III and the rest of the world, there will be an even greater communication delay on planetary surface missions that will complicate remote support. The communication signal to Mars takes a maximum of approximately 22.2 min to travel one-way, whereas to the Moon it takes only a maximum of approximately 1.35 s to travel one-way. [2]

For this reason, communication with operators of a lunar greenhouse will be similar to communications for EDEN ISS. For missions to Mars, though, operator autonomy from Earth needs to be increased by providing even more extensive training to astronauts in mockups on Earth and pre-defined procedures for various scenarios, including emergencies. At the same time, the level of automation of operation processes must be increased (e.g., using robots). AI, VR to refresh knowledge during space missions, or AR to facilitate operations could be used.

Despite these differences, the workload measurements described in this chapter can provide inferences for the values for planetary surface greenhouse operations and can be used as a basis for planning and developing mission scenarios, operational procedures, or system architectures.

4.5.1 Comparison of Workload Values

Overall Workload Scores

The workload investigations in this chapter have indicated a slightly increasing overall workload score from October (51.2) through November (61.2) to December (64.0) for the monthly workload measurements. These values are nearly identical to the weekly workload measurements with mean values for October (53.3; SEM=6.18) through November (59.8; SEM=6.86) to December (66.8; SEM=4.37). These overall workload score values are nearly twice the size of values measured for the OOT for the 2019 mission with 39.8 (SEM=5.5) and 2020 mission with 37.7 (SEM=5.8) [2].

There were no specific winterers during the 2019 and 2020 missions dedicated to the operations of the MTF, such as in the 2021 mission. Instead, members of the wintering crew volunteered to operate the MTF mainly to provide fresh food in addition to some scientific investigations. Five winterers operated the MTF during the 2019 mission, and nine winterers operated the MTF during the 2020 mission. The OOT for the 2019 mission completed workload measurements for their full wintering expedition at the end of their stay in Antarctica, while the OOT for the 2020 mission completed workload measurements during the first months of their wintering expedition and also for the full set of tasks for operating the MTF. The OOTs for the 2019 and 2020 missions had no horticultural experience and were unfamiliar with the MTF systems at the beginning of their wintering expeditions. Thus, an RST at DLR's MCC in Bremen supported these OOTs. The RST planned activities, monitored the MTF from Bremen, and suggested decisions and recommended solutions for off-nominal events. [2] This decreased the responsibility and, thus, the mental and temporal demands of the OOTs. This could explain why the overall workload measurements for the OOTs in the 2019 and 2020 missions are so much lower than for the operator in the 2021 mission, who was more independent from the RST in Bremen and collected a much larger and more diverse amount of data. Conversely, the RST in the 2019 and 2020 missions had a mean overall workload score of 67.5 (SEM=4.5) [2], which is in a similar range to the December value of the operator during the 2021 mission. The SMT 2019/2020, a team of experts regarding the MTF systems and operations, had a slightly lower overall workload score of 54.5 (SEM=3.5) [2].

With the analysis by Grier [140] of over 1000 overall workload scores based on 200 publications, it is possible to evaluate if an overall workload score should be considered high or low. The overall workload score analyzed shows a minimum value of 6.2 and a maximum of 88.5. The performance of the participants was not considered. [140] However, no statement can be made as to whether an activity can be perceived as acceptable based on the overall workload score alone, as this also depends on the perception of the context by the task operator [141].

The overall workload of the operator in the 2021 mission was higher for October than 50% of the values presented in Grier [140], higher for the monthly measurement in November than 75% of the values, higher for the mean of the weekly measurements in November than 70% of the values, and higher for December than 80% of the values. The benchmark for above 75% is at an overall workload score of 60.0 [140], which is nearly reached by the average of the weekly measurements in November.

Adjusted Ratings

The measurements of the adjusted ratings of the monthly measurements for a full set of tasks (Table 4.5) and the mean of the weekly measurements (Table 4.6) show similar adjusted ratings with some outliers. It can be seen that the mean value of temporal demand has the highest value among the six dimensions and is increasing in the latter weeks (Table 4.7). This is followed by equally high mean values for mental and physical demand. The mean adjusted ratings for performance and effort rank third. The lowest mean values are measured for frustration.

Compared to the adjusted ratings presented by Zeidler *et al.* [2], it can be seen that the highest values of the OOTs in the 2019 and 2020 missions were also measured for temporal demand. Nevertheless, these values reach just half of the mean adjusted rating for temporal demand of the operator in the 2021 mission. The second highest values of the OOTs in the 2019 and 2020 missions were measured for effort [2], with slightly higher values compared to the operator in the 2021 mission. The adjusted ratings for mental demand, physical demand, and performance of the OOTs in the 2019 and 2020 missions show similar values in relation to each other and are in third rank [2]. Compared to the operator in the 2021 mission, mental and physical demands are nearly half and the performance is similar. The lowest values are measured for frustration for all three missions.

Specific Recurring Tasks

The overall workload score of 45.0 from Grier [140] was used as benchmark to determine which of the tasks in Table 4.10 should be supported or simplified. This benchmark value is higher than 40% of the values analyzed by Grier [140]. In the Cultivation category, the overall workload values for harvesting Red Giant pepper (51.0), Rosie pak choi (53.7), and Dolly Genovese basil (59.3), as well as seeding (48.0) are above the benchmark value. The scores for harvesting Red Giant pepper and Rosie pak choi are above 50%, and harvesting Dolly Genovese basil is above 70%. In the Maintenance category, the overall workload scores for cleaning (45.4; SEM 3.43), shoveling MTF (48.8; SEM=14.83), fresh water tank filling (48.8; SEM=7.83), plant checks (54.0), and nutrient solution preparation (57.3) are all above the benchmark of 40%, with plant checks and nutrient solution preparation even above 60%. In the Science category, microbial sampling (52.9; SEM=5.87) and data review (46.1; SEM=6.01) are above the benchmark of 40%, with micro sampling above 50%. In the Miscellaneous category, return freight organization (52.2) and public outreach (54.0; SEM=8.67) are above the 40% benchmark, with return freight organization even above 50% and public outreach even above 60%.

All these tasks should be supported or simplified for operations in a space greenhouse.

4.5.2 Recommendation

The results of this chapter indicate the need to minimize the workload of the on-site operator in a space analog greenhouse. Reducing operator workload will require setting attainable goals for the operator output in terms of tasks and responsibilities. As seen during the 2021 mission compared to the 2019 and 2020 missions, having a single crew member operate the greenhouse with support from the RST – a dynamic we also expect for future long-duration spaceflight missions – can contribute to a greater overall workload. Thus, future space greenhouses should integrate automation, robotics, VR and AR, and other technologies to support with tasks such as cleaning, nutrient solution preparation, monitoring plants, seeding and harvesting. Automating or reevaluating the amount of data and samples collected for science could also decrease the workload associated with harvesting and activities in the Science category.

Although some tasks, like MTF shoveling, were specific to Antarctica, we anticipate that future space greenhouses will have tasks unique to the particular location and mission. It will also be crucial to account for more off-nominal events such as failures of equipment in terms of expectations from the operator. Therefore, operator workload and its relationship to crop production and the overall contribution to mission success on the Moon and Mars will be dependent upon optimizing what can be accomplished by the operator and by assisting technologies.

The investigations presented in this chapter could serve as a basis for the planning and design of future lunar and Martian space greenhouse systems.

Chapter 5

Augmented Reality Interface

2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)

ARCHIE²: An Augmented Reality Interface with Plant Detection for Future Planetary Surface Greenhouses

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Keywords: EDEN ISS, Augmented reality, ARCHIE², Greenhouse, Space analog, Operations, Crew time, Workload.

1 Introduction and Motivation

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The investigations presented in the first part of this thesis have raised new research questions, which are summarized in **RQ3** and **RQ4**. The second part of this thesis addresses these research questions through computer science investigations.

Therefore, a concept for an AR interface called ARCHIE² is presented in Chapter 5. This interface simplifies the work processes of OOTs and RSTs involved in future space greenhouse operations to reduce workload and crew time (**C5**). With the ARCHIE² AR interface running on an AR headset, it is possible to visualize support features for greenhouse operations, such as operational procedures and status information on plants, technical systems, or environmental parameters, allowing for hands-free operations. The research conducted demonstrates the significant benefits of AR applications to the operations of future space greenhouses (**C8**).

As part of the ARCHIE² AR interface, a new tool that runs directly on an AR headset for real-time plant detection and augmentation of plants with plant-specific information was developed (**C6**). The implementation and performance of the plant detection and augmentation method are described in detail in this chapter.

The results presented on the ARCHIE² AR interface, as well as the implementation and performance of its plant detection and augmentation tool, provide essential benchmarks for extending the limited research in this area (**C5**, **C6**) relevant for both space and terrestrial applications.

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5.1 Introduction and Motivation

In the Global Exploration Roadmap [6], 14 space agencies expressed a common interest in expanding human presence into the solar system to reach Mars. As preparation for a crewed mission to Mars, humans are planning to revisit the lunar surface by the end of this decade and establish sustained research infrastructures [145]. From the mid-2030s onwards, long-duration lunar habitats will be established on the Moon [145]. Planetary surface greenhouses to produce plants will be an integral part of these habitats to reduce the number of expensive transport flights needed for food resupply from Earth and achieve higher independence from Earth. In addition, plants in such greenhouses will be used to produce food, process air, recycle water [10], and increase the astronauts' psychological well-being [11].

In early 2018, the space analog EDEN ISS greenhouse was established in Antarctica near the polar research station NM III, operated by the AWI as part of the EDEN ISS project. The EDEN ISS project aimed to investigate key technologies for planetary surface greenhouses under Moon/Mars analog conditions [34]. Studies such as these are needed as baseline work for operating planetary surface greenhouses on the Moon and Mars. During the four one-year analog missions in Antarctica, numerous studies have been conducted on food quality and safety, microbiology monitoring, PHM techniques, human factors, horticultural sciences, as well as resource consumption and waste production analysis. In addition to these investigations, a significant focus was put on examining crew time, workload, and interaction between the OOTs and the RSTs on Earth.

In space missions, crew time is a valuable and limited resource [40] and needs to be optimized as best as possible [32]. Repairs and maintenance activities account for a substantial portion of the overall crew time required for a space mission [41]. To have more time for scientific activities, the crew's time for repairs and maintenance activities has to be reduced [40]. This has also been confirmed by experience from the space analog EDEN ISS missions [48]. These missions have shown that the required crew time and the specific workload demand for operating a planetary surface greenhouse by on-site operators (astronauts) and RSTs on Earth must be reduced for future space missions [2].

By augmenting the field of vision of the user with interactive virtual elements, AR applications, in general, could increase compliance with procedures [86] and reduce errors in the execution of operational activities, resulting in fewer failures and delays [85, 86]. This in turn could increase the user's efficiency [72] and the accuracy of executed tasks [72, 86], resulting in reduced overall crew time [72, 85, 86] and workload for the user [85]. In addition, the virtual interaction with input and output options of the interface could result in an abandonment of keyboard entries or paper documents while working on a task, enabling hands-free operations [70, 72, 86].

All these benefits of AR technology could also apply to the use of AR in the operations of a planetary surface greenhouse. However, using AR applications in such a system can reduce not only crew time and workload of the on-site operators (astronauts) but also of RSTs on Earth while increasing the safety of on-site operators and plants. Moreover, using AR could lead to facilitated training processes, reduced training needs [86] for new operations in such a greenhouse or as needed, resulting in increased autonomy [86] of the on-site operators from Earth support and facilitated integration processes of untrained personnel into planetary surface greenhouse operations [2]. Increased autonomy is particularly important for missions beyond LEO, as remote support can be reduced due to cost and communication delay [73], especially in the case of Mars, with a delay of up to 22.2 min one-way [2]. Also, the loss of knowledge due to the substantial time gap of more than 18 months [87] between the actual space mission and the astronaut training completed on Earth can be countered using AR during the mission.

Therefore, in this chapter, we present the concept of an AR interface (Figure 5.1) called ARCHIE². ARCHIE² is designed to facilitate the operations of future planetary surface greenhouses by visualizing status information on plants, technical systems, and environmental parameters in the greenhouse on an AR headset. Furthermore, schedules, procedures, various planning tools, or an integrated remote assistance tool can be displayed. [91, 146]

The key contribution of this chapter is the concept of an AR interface supporting the operations in a planetary surface greenhouse and the implementation of its plant detection module running locally on the AR headset. We provide details on the implementation as well as the performance of the plant detection and augmentation process. The research presented in this chapter could serve as a proof of concept that plant detection can be achieved with an application running directly on an AR headset, and the results could serve as a benchmark for future studies in this area.

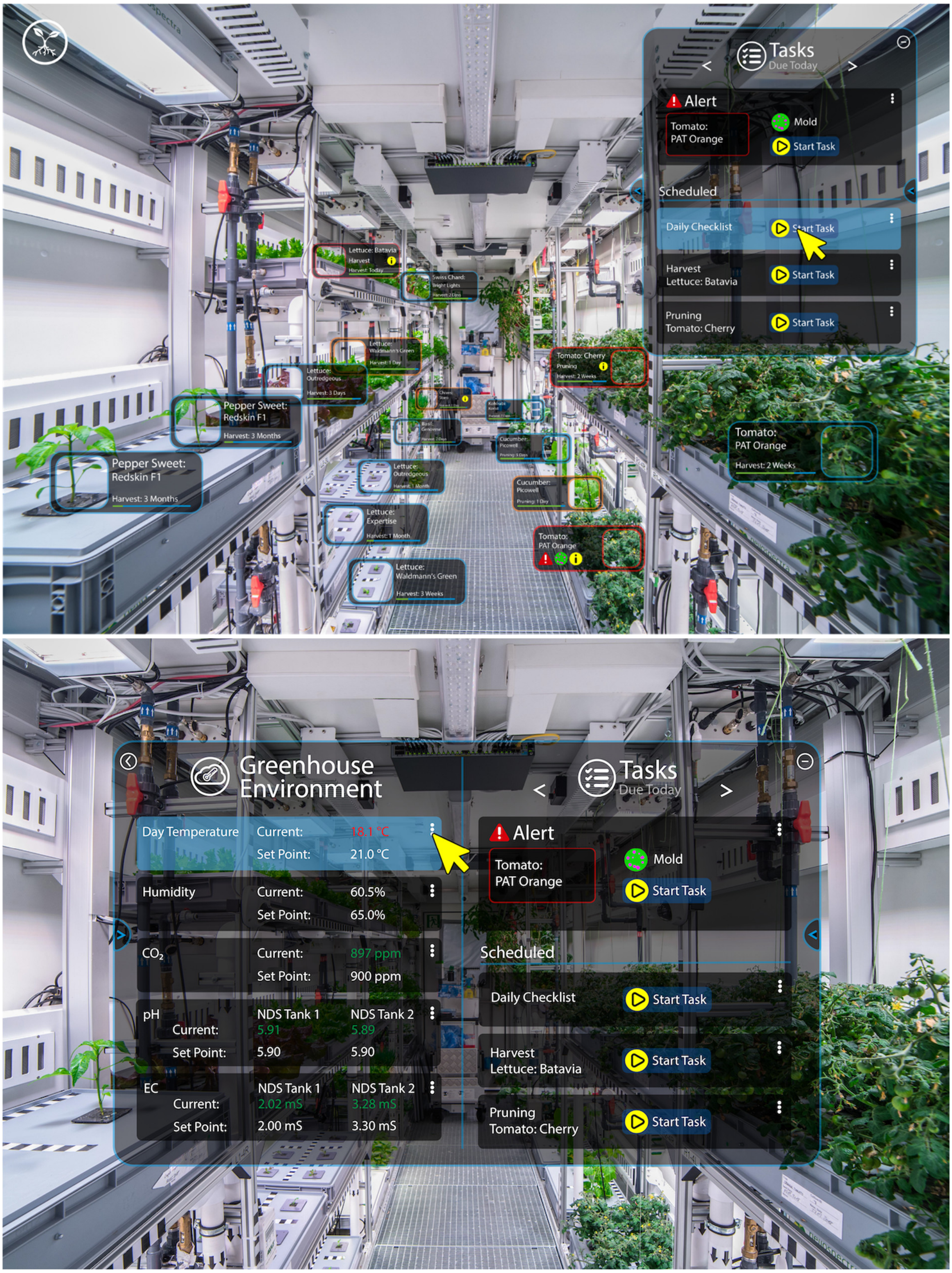

Figure 5.1: Concept of the ARCHIE^2 augmented reality interface: Exemplary user view on the augmented reality headset showing the scheduled tasks and plants inside the EDEN ISS greenhouse augmented with labels visualizing plant-specific information (left); Greenhouse Environment submenu (right). The yellow mouse pointer only illustrates a selection action on the interface (not part of the prototype). [91] Photo credits: Hanno Müller.

5.2 Related Work

AR use can be spread widely in various fields of application due to individual adaptability. Some examples for use on Earth are the use in medicine [58], textile industry [147], aerospace industry [62], water management [148], navigation/tourism [58, 62], urban planning [58], livestock farming [65], gaming industry [58] or education/training [58]. A growing number of AR applications also exist in the agriculture or space sector.

Some agricultural and space applications, which share similarities to the operations of planetary surface greenhouses, are presented in the following.

5.2.1 AR Applications for the Terrestrial Agricultural Sector

Katsaros and Keramopoulos [149] developed a prototype application named FarmAR. The application identifies plants and displays plant-specific information on a mobile device, such as their common name, scientific name, and notes about their cultivation. This information is used to augment the reality of the live camera view. In addition, information about common diseases and environmental parameters is visualized. [149, 150]

Neto and Cardoso [151] developed an AR prototype, which can be used on smartphones as an early warning system for a potential fungal infestation in tomato plants with Botrytis cinerea. Furthermore, crop-related information such as crop type or sowing date, environmental conditions, and the irrigation schedule can be visualized. [151]

Another prototype application in the agricultural sector was developed by Nigam *et al.* [152]. It aims to support farmers with little knowledge of entomology using an Android application on their mobile devices to precisely define the infestation of insects on their crops and identify possible countermeasures. [152]

Shaleendra *et al.* [153] designed an Android-based AR prototype called AR-Glasshouse that allows greenhouse operators to visualize how their greenhouse could be automated and the potential benefits of automation. [153]

Bekiaris *et al.* [154] developed an application called Greta that can be used to monitor and control intelligent greenhouses. It has an AR application part, which can be used on handheld devices to display greenhouse status information such as grown plants, their condition, and environmental conditions. Moreover, hardware in the greenhouse can be controlled via controls visualized in AR. [154]

All mentioned applications are still individual pioneers and have not yet been broadly used in the agricultural sector. Additional examples of applications in the agricultural context can be found in the literature review conducted by Hurst *et al.* [84].

5.2.2 AR Applications for Space

AR can also be used in various space application areas. For example, it could be used to artificially augment the constrained habitat volume [155, 156], support early design phases for space hardware [157–161], support planetary research [162, 163], support space hardware assembly, integration and testing activities [74, 164, 165] or support astronaut training on Earth [166–169]. It can even be used for surgical training or medical emergencies during long-term space missions to provide medical instructions and guidance to astronauts with only basic medical training [164, 170].

The more detailed examples below share similarities to the activities in a planetary surface greenhouse.

Astronaut Support in Space

Additionally, AR can be used to support astronauts on space stations such as the ISS during their daily work to reduce crew time, increase astronaut efficiency [171], and enable hands-free operations [68, 70].

In 1998, Agan *et al.* [68] published a paper in which the function of a wearable computer coupled to a head-mounted display (HMD) with AR functions was presented. The so-called WARP system of NASA, intended for use on space stations, is designed to enable the display of text and images as well as measured biosensor data by the system and real-time audio/video communication via the HMD. [68] [69]

The WEAR project funded by ESA investigated how location and context-sensitive information can be visualized and managed on an AR system. Astronauts could look at checklists, execute procedures, and get additional information when needed. [70, 71]

Another assistance tool funded by ESA, which was already tested on the ISS in 2015 is the mobiPV. The main task of this system was to display procedures to the astronauts and support them during the task execution. [72–74]

In a follow-up project funded by ESA called EdcAR, the data provided by the mobiPV system was visualized in AR using the EPSON Moverio Pro BT2000. [75]

Markov-Vetter [169] also investigated how AR-based assistance systems should be designed to support and simplify the work of astronauts onboard the ISS, for example, when working with payloads. For this purpose, the Mobile Augmented Reality for Space Operations (MARSOP) system was developed and field tested. [169]

Building on the experience gained during NASA's Sidekick project [76, 77], with the goal of using Microsoft HoloLens to virtually assist astronauts onboard the ISS in performing procedures and enabling remote support from Earth, NASA's T2AR project [78, 79] demonstrated the use of

Microsoft HoloLens for maintenance and inspection of science and training equipment without support from Earth during ISS Expeditions 64 and 65.

Another topic studied is how AR can be used in future planetary missions, such as on the Moon (e.g., as part of the Artemis campaign). For example, Ahsan *et al.* [80] developed the ARGOS system using it for future training or in operational environments to make EVAs safer, more effective, and more efficient. [80]

Greenhouses in Space

Since plant cultivation will be an integral part of future space missions, Bhardwaj *et al.* [172] presented an idea at a very basic theoretical level to use multiple robots to interact with plants and maintain bioregenerative life support (e.g., harvesting) in a sealed and controlled part of a spacecraft to reduce the exchange of pathogenic microorganisms between plants and astronauts. For this purpose, the cultivation area is projected into AR. The astronaut's hand gestures are tracked and replicated to control robotic manipulators in the sealed cultivation chamber. However, the main focus of this study was on the design of the spacecraft. [172]

The literature review in this chapter has shown that AR applications, despite their multiple potential uses and far-reaching benefits in supporting work processes, have very limited and non-standardized prototypical applications in the greenhouse context on Earth. Xi *et al.* [83] and Hurst *et al.* [84] also confirm that despite the widespread use of AR, there is still a huge need for research on AR in the agricultural sector, also evidenced by the low number of publications in this research area especially with respect to AR in greenhouses.

When considering the general use of AR during space missions, it should be noted that some of the prototypes mentioned have already been tested in space missions, but none of them are standardized. With respect to the use of AR to support plant growth under space conditions, it was shown that apart from the publication of Bhardwaj *et al.* [172], we are not aware of any other studies on the use of AR or even the practical implementation of AR applications in space greenhouses.

Therefore, a reliable comparison of new AR applications for lunar surface greenhouses with existing ones is hardly possible. There remains an immense need for research to evaluate whether the use of AR in the context of plant cultivation in space is beneficial and could help astronauts in their operations of greenhouses during future space missions, reducing their crew time and workload and that of the RSTs on Earth.

5.2.3 Agricultural Plant Object Detection

The deep learning algorithm You Only Look Once (YOLO) [173] is used for object recognition in various domains. YOLO-based detectors with many advancements (e.g., YOLOv3) and modifications (e.g., R-YOLO) have been proven to be effective for recent applications in agricultural contexts.

Zheng *et al.* [174] compiled a plant detection dataset of 31,147 images called CropDeep, displaying different crops in varying lighting conditions, growth phases, and camera angles in order to train an object detector that could be used in future applications such as picking robots. A comparison among different object detectors on the CropDeep dataset resulted in a recommendation of the YOLOv3 network as it outperformed other object detectors (e.g., Faster R-CNN, SSD, RFB, YOLOv2 or RetNet) in the combination of detection accuracy and speed. It reached a mAP@[0.5] (mean average precision) of 91.44 while performing at 40 FPS. [174]

Yu *et al.* [175] describe how an adjusted YOLO implementation named R-YOLO is utilized to construct a strawberry harvesting robot. The embedded controller on the robot (NVIDIA Jetson TX2) can process 18 640x480 pixels images per second, which is described as an excellent real-time performance by the authors. R-YOLO is reaching an overall precision of 94.43%, and the picking robot manages to pick strawberries with a success rate of 84.35% in a harvesting field test. [175]

Another design for a tomato-picking robot system is based on the YOLOv5 framework [176]. YOLOv5 detection is combined with a depth camera to determine the three-dimensional coordinates at which the robot can pick the tomato. A set of 1,645 tomato images was collected and used to train the YOLOv5s deep learning model. The network was able to process one image in 104 ms on average, which corresponds to a frame rate of 9.62 FPS. [176]

All these contributions show the prevalence of the YOLO framework in agricultural plant detection tasks, which underlines the decision also to make use of the YOLOv5 framework for plant detection in this work. In the context of this chapter, no publications could be found that used an AR headset combined with plant detection in a greenhouse environment.

5.3 ARCHIE²: AR Interface for a Planetary Surface Greenhouse

A research goal of the EDEN ISS operation scenario investigations was to develop and investigate processes for higher plant cultivation [57]. As mentioned previously, research [2, 48] and experience gained during the EDEN ISS missions in Antarctica concerning the operations of a space analog greenhouse have indicated that crew time and workload demand of the operation teams of a planetary surface greenhouse needs to be optimized to enable future space missions with integrated planetary surface greenhouses.

Based on these investigations, five possible application areas: the display of technical greenhouse information, display of plant-specific information, display of planning tools, communication tools, and document processing functions (Table B.1 in Appendix B) are derived for implementation in an AR interface, to support on-site operators of planetary surface greenhouses and RSTs on Earth [146]. Using these application areas and the EDEN ISS operation procedures, the ARCHIE^2 AR interface concept was developed to facilitate working processes used for planetary surface greenhouse operations and presented in Zeidler and Woeckner [146] based on the preliminary work of Woeckner [91].

5.3.1 Structure and Functions of the Design

The ARCHIE^2 AR interface consists of the main menu (Home Screen and Tasks menu) and five submenus: Greenhouse Environment, Plant Environment, Communication, Documents, and Settings (exemplary images in Appendix C). By starting ARCHIE^2 on the AR headset, the greenhouse on-site operator is presented with the Home Screen and Tasks menu. From the Home Screen, it is possible to access the submenus. The Tasks menu is used for visualization and rescheduling of scheduled activities and accessing related plant-specific procedures. In addition, it lists all existing alarms in the greenhouse. [146] Figure 5.2 shows the screen flow of the ARCHIE^2 AR interface with the functions of the specific menu/submenus.

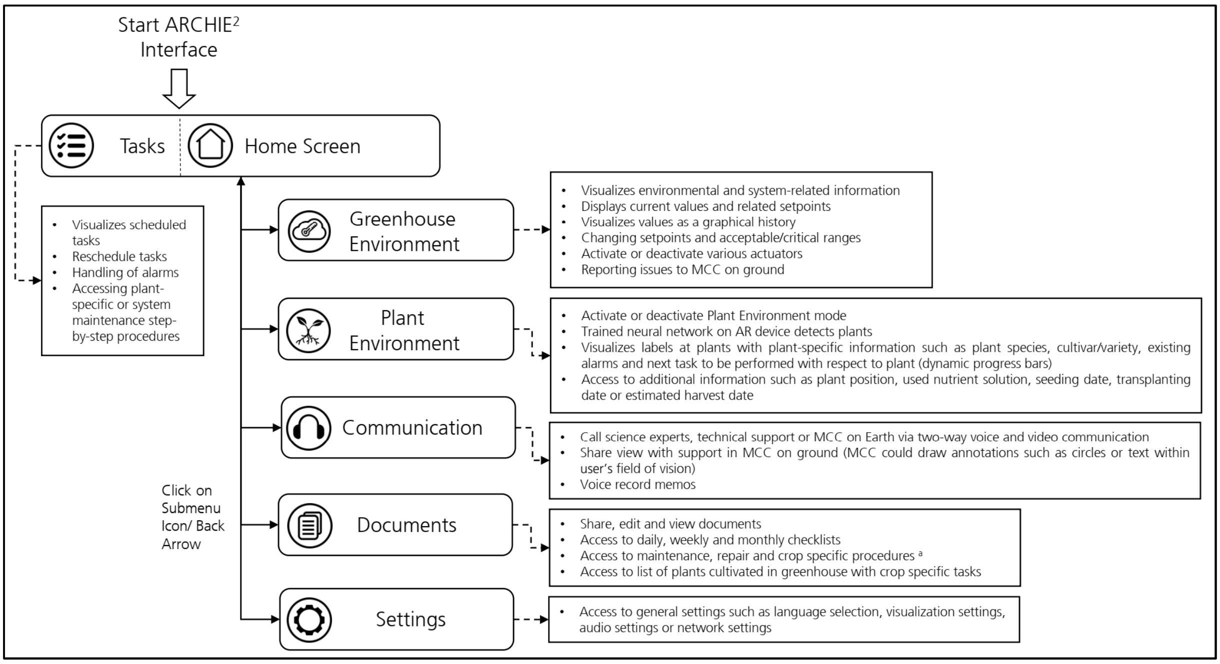

Figure 5.2: Screen flow of the ARCHIE^2 augmented reality interface and functions of the interface sorted by dedicated menu/submenus. [a] Information about which operation is being processed and which step is being performed by the operator is automatically shared with the support team on ground. MCC = Mission Control Center; AR = augmented reality.

5.3.2 Greenhouse Environment

The Greenhouse Environment submenu visualizes all relevant environmental and system-related parameters in the greenhouse and actuator data. Current values and related setpoints are displayed. The user can manually modify setpoints and activate or deactivate the various actuators. [91, 146]

5.3.3 Communication

In the Communication submenu, the user can approach various points of contact, such as science experts, technical support, or the MCC on Earth via an integrated two-way voice and video communication interface for assistance in preparing or performing tasks in the greenhouse. It is possible for the interface user to share the view with the support on ground, who then can draw annotations such as circles, arrows, or text within the user's field of vision. [91, 146]

5.3.4 Plant Environment

By clicking on the Plant Environment submenu on the Home Screen, the Plant Environment mode can be activated/deactivated. An activated Plant Environment mode is symbolized by a white icon in the upper left corner of the user's field of vision (Figure 5.1), which can also be used by clicking on it to toggle the Plant Environment mode. [91, 146] In activated Plant Environment mode, plants are detected by a trained neural network using the plant detection module of the Plant Environment submenu on the AR headset by evaluating the camera video stream. Furthermore, labels on the plants in the greenhouse are activated in three-dimensional space. Dimensions and coordinates of the detected plants are used to display corresponding labels, visualizing plant-specific information such as plant species and cultivar/variety.

To minimize the scope of additional organizational tasks for the users, such as manual marker placement, the solution approach of fully automated plant detection by machine learning (ML) was chosen. Compared to the use of optical markers or virtual markers in three-dimensional space, which store the plant-specific information, no markers need to be manually moved when a plant changes location. In addition, no misplacement of labels could occur because the position of the labels does not need to be approximated near the aeroponically/hydroponically grown plants due to the plant detection process. Furthermore, the markers cannot become soiled or obscured, as is the case with optical markers. [177] Furthermore, plant detection could be the first step toward a more sophisticated system that continuously supports the user in the greenhouse. More advanced algorithms could use granular plant detection to guide the user in pruning the correct parts of the plant through visual markers or to assign additional information to plants, such as detected diseases or the maturity of a particular fruit.

If several plants of the same cultivar/variety are grown in various locations in the greenhouse, information such as three-dimensional coordinates of the detected plant would be needed in addition to its cultivar/variety to specify exactly which plant is meant and visualize the correct plant labels. If the coordinates are not yet stored in the system, a new instance for coordinates and cultivar/variety is automatically created in the system. Thus, the plant information stored in the system can be uniquely assigned and displayed to the user upon detection. [177]

In addition, the plant-specific information is complemented by additional information such as existing alarms, visualized as icons, and the next task to be performed concerning the specific plant, which is displayed with a dynamic progress bar illustrating the time remaining until then. Example tasks could be harvesting, transplanting or pruning plants. A window with additional plant-related data such as plant position, used nutrient solution, seeding date, transplanting date, or estimated harvest date can be opened by clicking the corresponding plant label. For this purpose, the ARCHIE^2 AR interface is coupled with a database on a server where this information is maintained by the on-site operators of the greenhouse. Furthermore, colored frames indicate the urgency of activities on the specific plant. Blue frames visualize that no task is to be performed today or tomorrow. Orange ones indicate a task to be performed tomorrow, and red ones today. [91, 146]

5.3.5 Documents

The Documents submenu gives the user access to various pieces of information and documents, such as checklists and procedures used in the greenhouse. Furthermore, a list of all the plants cultivated in the greenhouse with plant-specific information can be accessed. All procedures and checklists are presented on the AR display as step-by-step instructions with additional explanations/information and the option to call for support from MCC on Earth. During the execution of a procedure, it is also possible to record notes or take photos for documentation. Information about which operation is being processed and which step is being performed by the operator is automatically shared with the support team on ground. [91, 146]

5.4 Implementation of the Plant Environment including its Plant Detection Module

Based on the special conditions of a lunar surface greenhouse, the Plant Environment submenu (Subsection 5.3.4) represents a central feature of the ARCHIE^2 AR interface. For this chapter, the Plant Environment submenu with its plant detection module was implemented on an AR headset (Microsoft HoloLens 2).

The steps required for this are: (1) Object detection model selection, (2) Baseline dataset preparation, (3) Iterative training process and preparation of plant detection model for arugula selvatica, and (4) Implementation on HoloLens 2. The following explanations are based on the work of Klug [177].

5.4.1 Object Detection Model Selection

Given the realization of the plant detection, it is necessary to train an artificial neural network accordingly. The implementation of plant detection in this chapter mainly relies on the YOLOv5 framework [178]. We refrain from creating another plant detection model or using other frameworks since the successful integration of YOLO-based models in the plant detection context has already been proven by various publications [174, 179].

As a result of the limited computational power of HoloLens 2, the pre-trained, 283-layer, YOLOv5s deep learning model was trained for plant detection. It was the smallest and fastest model of the YOLOv5 framework at the time of training start, resulting in potentially higher performance and, accordingly, a potentially better user experience on the HoloLens 2. The YOLOv5s model was pre-trained on the Microsoft Common Objects in Context (MS COCO) dataset [180].

Furthermore, the automatic scaling function of the YOLOv5 framework was used for the images. In addition, the default settings of the data augmentations of the YOLOv5 framework were used during training to achieve robust plant detection even with a small number of training images.

5.4.2 Baseline Dataset Preparation

To train the neural network for use in the context of the EDEN ISS greenhouse, we used a baseline dataset of 731 annotated images. Of these, 314 top-view and 334 side-view images showing arugula selvatica plants in various development states and under relevant lighting conditions, as well as images of other plants and entirely without plants were used from the EDEN ISS greenhouse (Figure 5.3). This was done since no large datasets of arugula selvatica plant images were freely available.

The EDEN ISS images were taken from the fixed-mounted cameras during the period from 2018 to 2021 inside the EDEN ISS greenhouse. Two different camera models were used: HIKVISION DS-2CD2542FWD-I 4MP with an image resolution of 2688×1520 pixels and HIKVISION DS-2CD2185FWD-I(S) 8 MP with an image resolution of 3840×2160 pixels.

Images of arugula selvatica were used because the plant does not form fruits or flowers due to early harvesting, and therefore few morphological changes are observed during growth.

Figure 5.3: Exemplary neural network training images: ***(A)*** *EDEN ISS side-view image showing arugula selvatica plants;* ***(B)*** *EDEN ISS top-view image showing arugula selvatica plants;* ***(C)*** *EDEN ISS greenhouse image without plants;* ***(D)*** *EDEN ISS top-view image showing Brassica rapa ssp. narinosa plants.*

Due to limited perspectives and sometimes quality of the side-view images, the baseline dataset was additionally extended by 83 arugula selvatica images from external sources such as plantnet.org and images.google.com.

In Figure 5.3, white rectangles (upper left corner of images A and C) can be seen covering parts of the image. These manually created maskings hide the time stamp of the cameras and readable labels on the shelves inside the greenhouse. This was conducted to prevent the neural network being trained from using the letters and numbers as features to detect arugula selvatica.

5.4.3 Iterative Training Process and Preparation of the Optimized Plant Detection Model

To obtain a model for detecting arugula selvatica within the EDEN ISS greenhouse, different datasets were formed using subsets of images of the baseline dataset (Subsection 5.4.2) to be used for training the YOLOv5s model. The datasets were modified in an iterative process by augmentation of images, which was applied in addition to the augmentations from the YOLOv5 framework, adding images, or changing the annotations to investigate the effects on the training results.

The basis for the modification of the datasets was a comparison of the performance metrics mAP@[0.5:0.95], object loss and box loss, as well as a review of the images annotated by the models to achieve robust plant detection of arugula selvatica from multiple perspectives.

For each iteration of the dataset, at least one training run was performed. The model was always untrained at the beginning of each run. Therefore, the starting point was the same for all runs.

Before each training run, the datasets were split into training and validation sets. The validation set was unknown to the trained model, ensuring that the model was generalizing and did not learn the specific features of the training data.

At the beginning of each training run, the training configuration values were manually set: on which image size, with which batch size, and over how many epochs the model should be trained. The YOLOv5 hyperparameters, such as momentum, initial learning rate, or weight decay, were set to default parameter settings for training as described in Jocher [181]. Following an epoch, the performance metrics of the model trained up to that epoch were calculated for the training and validation set. This allowed a comparison to be made between the performance of the model on known data and unknown data to evaluate whether the model was generalizing. After each batch of images, the weights of the YOLOv5s model were adjusted based on the achieved loss values to minimize the overall loss function.

The composition of the dataset selected to train the model used on an AR headset can be seen in Table 5.1. The composition of the other datasets and the corresponding evaluation of the training results can be found in Appendix D.

Table 5.1: Composition of the dataset selected to train the model used on an augmented reality headset for arugula selvatica detection. [a] Images without arugula selvatica are from various perspectives. [177]

Source of Images	Content of Images	Number of Images	Number of Annotated Instances
EDEN ISS Greenhouse	Top-view with arugula	618	10,510
	Side-view with arugula	668	1,182
	Without arugula [a]	57	0
External	Various	67	110
Total		**1,410**	**11,802**

The configuration values for the training of the dataset selected for the model used on an AR headset were set to an image size of 320×192 pixels, a batch size of eight, and 300 epochs. The resolution of the processed images was 320×192 pixels, scaled by the YOLOv5 framework. The 320×192 pixels resolution was the largest possible resolution that resulted in a good usable application on a laptop[b] and was determined by successively decreasing the model size, with subsequent testing on the laptop.

In addition, Zheng *et al.* [174] reported good crop detection results on a similarly sized model (300×300 pixels), a YOLOv3 neural network trained with their CropDeep Agricultural Dataset. In

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[b] Results achieved with a laptop equipped with an AMD Ryzen 7 5800H processor and a GeForce RTX 3060 graphics card.

the following, this model is referred to as the YOLOv3 CropDeep model. The trained and optimized 320×192 pixels plant detection model, hereafter referred to as the arugula model, detects arugula selvatica as one class.

5.4.4 Implementation

The ARCHIE^2 plant detection module using the arugula model is implemented on the HoloLens 2 using Microsoft's Mixed Reality Toolkit (MRTK). Unity and the Barracuda framework are used for the integration of the trained neural network. Since the plant detection by the neural network has to be executed on the main thread within the Unity application, the computations required for this are split across multiple frames. Otherwise, the main thread would be blocked, resulting in performance degradation.

The architecture (Figure 5.4) consists of three modules: the MediaCapturer, the Neural Network Manager (NNManager) and the LabelRenderer.

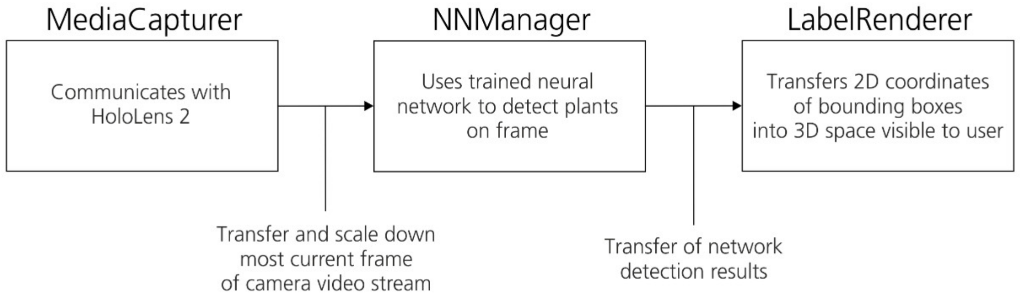

Figure 5.4: Prototype architecture with functions of its modules. Neural Network Manager (NNManager). Reproduced and modified from Klug [177].

The MediaCapturer module is responsible for communicating with the HoloLens 2 to transfer the current frame of the camera video stream to the NNManager. During this process, the resolution of the transferred frames is scaled down to the trained resolution of the neural network. Then, the NNManager performs the plant detection on the frame and forwards the results (i.e., the class labels of the detected plants and their bounding box coordinates) to the LabelRenderer. Subsequently, the LabelRenderer transfers the two-dimensional coordinates of the bounding boxes into the three-dimensional space visible to the user.

Augmentation labels (Figure 5.5) are placed at the three-dimensional location of the bounding box coordinates. The augmentation labels contain placeholders for the plant's name, the duration until harvest, and icons for status messages.

Figure 5.5: Augmentation label for the detected arugula selvatica plants with information on the name of the plant, the duration until harvest, and icons to draw attention to status messages. The label is visualized on the ARCHIE² augmented reality interface. [177]

As the plant detection application runs directly on an AR headset, only the five most likely detections on the frame of the camera video stream are visualized for the user to keep the prototype less cluttered. In future work, we will remove this limitation and add the capability to visualize unlimited labels with appropriate off-screen label visualization techniques (Figure 5.1). Hence, a maximum of five labels are displayed at the same time.

Furthermore, it is checked in each frame whether new and more likely plant detections of the neural network are available. In addition to updating the positions of the labels in each frame, the rotation of the labels in each frame aligns so that they face the user.

The user can deactivate or activate the plant detection. In the case of deactivated plant detection, the change of position and rotation of the labels and the deactivation of the labels stop. This allows the user to grab the labels and move them manually to more sufficient positions.

5.5 Evaluation and Discussion

The evaluation of the prototype is divided into performance tests, perspective tests, and accuracy evaluation.

5.5.1 Performance Test

The ARCHIE² plant detection module was launched locally on the HoloLens 2. No user was involved and no plants were observed during the performance test, as applying the plant detection process to any picture puts the same load on the processor of the HoloLens 2. Over 60 seconds, the achieved frame rates, metrics based on them (i.e., x% LOW values), and average inference times of the neural network were measured. Furthermore, the measurement was also performed on a laptop in the Unity editor to form a comparative value. These measurements can provide indications of possible performance improvements using future AR headsets.

Since the computations required for the plant detection by the neural network are split across multiple frames, a trade-off between performance and inference time is required to determine the lowest possible inference time of the model while maintaining a high performance of the ARCHIE^2 AR interface. Therefore, measurements were taken with a varying number of layers of the neural network computed within one frame to determine the maximum as well as minimum frame rates and inference times (Table 5.2).

Using the arugula model on the laptop, frame rates of 40 FPS were not undercut for up to 100-layer computations per frame. The inference time reached a value of 23 ms for 100-layer computations per frame.

Table 5.2: Results of the performance tests of the arugula model conducted on the HoloLens 2. A different number of layers of the neural network were computed within one frame. x% LOW is a measure for the average of all frame rates in the x-percentile (average of lowest frame rates). [a] The term computation indicates how many layers of the neural network are computed per frame. Reproduced and modified from Klug [177].

Device	Computations [a]	Average FPS	0.1% LOW	1% LOW	10% LOW	Inference [ms]
HoloLens 2	1	57.18	20.91	26.60	34.95	5,094.58
	2	49.91	14.17	22.94	32.25	2,890.10
	5	49.55	11.96	21.79	31.95	1,175.83
	10	48.21	9.76	21.50	31.95	602.17
	50	37.30	8.80	10.01	11.81	251.33
	100	40.12	4.93	5.11	5.45	207.62
	283	41.44	3.93	4.34	4.65	183.53

Discussion of the Performance Results

For the classification of the frame rates achieved by the ARCHIE^2 AR interface during the performance tests, a study from 2007 is used [182], which measured the performance of test persons within a first-person shooter computer game depending on different frame rates. The tasks to be completed by the test persons were the control of a virtual avatar, with mouse and keyboard, through an obstacle course and accurate shooting within the computer game. It was found that such games are almost unplayable up to a maximum of constant 7 FPS. The study found significant performance increases in the test subjects starting at 7, 15, and 30 FPS, with the maximum performance at 60 FPS. In addition, the measurements suggest that increasing the frame rate above 60 FPS does not provide much added value. [182]

As a result, the prototype is considered unusable up to a maximum performance of 7 FPS, limited usable between 7 and 30 FPS, and good usable from a constant performance of 30 FPS. The assumption of good usability from 30 FPS is supported by the elaboration on YOLOv4 of Bochkovskiy *et al.* [183], in which models with at least 30 FPS were called real-time detectors.

Zheng *et al.* [174] also described a frame rate of similar magnitude (40 FPS) for the YOLOv3 CropDeep model as appropriate for crop detection tasks in an agricultural context, such as in greenhouses.

The maximum performance by computing one layer per frame on HoloLens 2 using the arugula model was at a 1% LOW value of approximately 27 FPS and a 10% LOW value of approximately 35 FPS, with an inference time of approximately five seconds. Since only one frame of the camera video stream was evaluated every five seconds at this inference time, this configuration is not practical.

In terms of higher performance and lower inference time, the results of the experiment with the calculation of ten layers per frame stand out. In this configuration, an inference time of 602 ms and an average of 48 FPS, a 10% LOW value of approximately 32 FPS, and a 1% LOW value of approximately 22 FPS were reached on the HoloLens 2. Thus, the 1% LOW value decreased by 5 FPS, and the 10% LOW value decreased by 3 FPS, but in return, the inference time decreased by 8.5 times compared to the results with a one-layer computation per frame. Accordingly, the HoloLens 2 prototype with the arugula model (320x192 pixels) could mostly be used well with 10-layer calculations per frame, although a constant 30 FPS was not achieved.

Limitations of the Performance Results

The significance of the performance results is limited by the fact that only by conducting a user study can it be concretely proven whether and from what level of performance the ARCHIE^2 AR interface is usable in plant detection.

The performance fluctuations can be reduced by temporarily deactivating plant detection. Plants detected up to that point remain augmented while performance normalizes to 60 FPS, which is the target frame rate of the HoloLens 2. Therefore, only short phases of activated plant detection are necessary to display the required information. Nevertheless, permanently turning the plant detection on and off could also have a negative impact on the user experience.

Further, the validity of the prototype's usability is limited due to the comparison with the study on first-person shooters [182]. Both the modalities of interaction and the goals of the application are different for the computer game and the prototype. It could be assumed that compared to the presented prototype, the impact of the achieved frame rates on the performance is higher for first-person shooters. This is because first-person shooters require high responsiveness, precision, and hand-eye coordination. Due to that, the prototype could already be considered consistently usable using the arugula model, as the threshold for good performance, in this case, could be lower than 30 FPS.

Similarly, the comparison with the frame rates of 30 and 40 FPS from the YOLOv4 model [183] and YOLOv3 CropDeep model [174] elaboration should be critically considered. Both elaborations did not justify why these values are sufficient for a real-time application and did not explicitly address AR applications with user interaction. In the context of this chapter, no references could be found that investigate the usability and performance parameters such as frame rates and inference times of AR applications using plant detection.

5.5.2 Perspective Test

The perspective test was conducted to check the practicality of the prototype and to test its capability of detecting a real arugula selvatica plant from different perspectives.

For the experimental setup (Figure 5.6), the plant was placed at three different heights (0 cm, 55 cm, and 110 cm) and viewed at each height from four different horizontal distances (25 cm, 50 cm, 75 cm, and 100 cm).

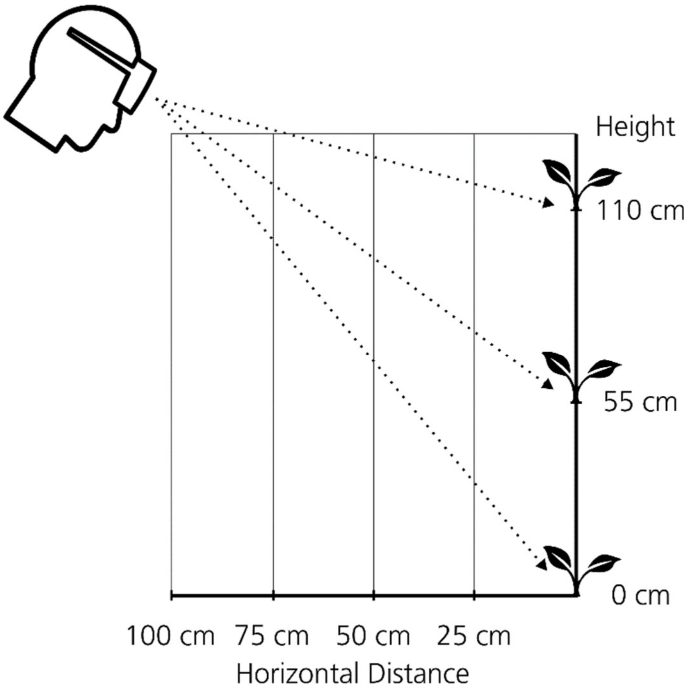

Figure 5.6: Experimental augmented reality interface setup for the perspective test. Reproduced and modified from Klug [177].

As a result, it was recorded whether or not detection and annotation occurred at the corresponding combination of height and distance. The HoloLens 2 was carried by a 184 cm tall test person throughout the entire test series. The positioning of the test person in front of the arugula selvatica plants was frontal and centered. The test person's gaze was directly on the plants at the various heights.

The results of the perspective tests show that the arugula model was unable to detect arugula selvatica plants at heights of 0 cm (placed on the floor) and 55 cm. The prototype detected and augmented arugula selvatica plants at a height of 110 cm up to a horizontal distance of 50 cm.

Discussion of the Perspective Results

The fact that the detection and augmentation of the plants only occurred when the user was in their vicinity slightly limits the usability of the prototype in a practical use case. New plants in the greenhouse would always need to be viewed at close range with the HoloLens 2 in order to detect the plants and link the plant labels with the actual 3D coordinates.

In the concept, the potential time savings of the HoloLens 2 compared to conventional methods is the main argument for its use. Therefore, the Plant Environment provides, among other things, the capability to visualize an overview near the plants of the planting date, the harvesting date, and which plants are currently in need of care. Once all the plants in the greenhouse have been detected, all the detections could be displayed based on their 3D coordinates, including the associated plant information mentioned previously. In this way, only the initial plant detection process would be somewhat limited.

Limitations of the Perspective Test Results

A limitation of the results of the perspective test is the composition of the dataset on which the model was trained for the plant detection of arugula selvatica and its impact on the evaluation.

The two camera models used are wide-angle cameras. The lens of the HIKVISION DS-2CD2542FWD-I 4MP has a focal length of 2.8 mm with a 106° angle of view, and the lens of the HIKVISION DS-2CD2185FWD-I(S) 8 MP has the same focal length with a 102° angle of view. The wide angle of view results in slight distortions of the image at its edges, which could also have a negative effect on the plant detection results since the focal length of HoloLens 2's photo/video camera is 4.87 mm +/- 5% and the angle of view is 64.69°.

The nature of the annotation within the training dataset may have contributed to the poorer plant detection results from a higher distance. During the annotation process, a bounding box was put around each arugula selvatica plant as accurately as possible. If the plants overlapped too much so that a clear assignment was no longer possible, several plants were annotated together within one bounding box, following the plant annotation recommendations of Zheng *et al.* [174]. By annotating each plant, the option was kept open to indicate procedures to be performed, such as pruning, precisely on a specific plant. This resulted in many very small annotations of plants and a low number of pixels within the bounding boxes. If all overlying arugula selvatica plants had been combined into one bounding box, regardless of whether individual arugula selvatica plants were detectable, then the bounding boxes for training would have been correspondingly larger. As a result, the arugula model (320x192 pixels) would also have had access to a larger number of pixels from which features could have been formed, which could result in better plant detection results.

5.5.3 Plant Detection Accuracy

The arugula model achieved a mAP@[0.5:0.95] value of 0.5368. The mAP@[0.5] value of the arugula model is 0.8731. Zheng *et al.* [174] reported a similar mAP@[0.5] value of 0.9144 for their YOLOv3 CropDeep model, which has a similar size (300×300 pixels) to the arugula model (320×192 pixels). Despite the slightly higher mAP@[0.5], it should be noted that the YOLOv3 CropDeep model considers different crops, which limits the comparison of mAP@[0.5]. The previously described mAP@[0.5] values are in a similar range to the RetNet crop detection network's mAP@[0.5] value of 0.9279, which is described as excellent accuracy [174].

5.6 Conclusion and Outlook

In this chapter, we reported on the concept of an AR interface that supports operational tasks to maintain future planetary surface greenhouses. In particular, the implementation and performance of its plant detection module, which runs locally on the AR headset for arugula selvatica plant detection and augmentation, was presented. Plant detection is feasible with an average frame rate of 48 FPS and an inference time of approximately 602 ms at a height of 110 cm up to a horizontal distance of 50 cm. The AR interface prototype demonstrated proof of concept that plant detection processes can be performed directly on an AR headset. Measurements of frame rates and inference times provide benchmarks for future research in that area. Moreover, the prototype could be used in terrestrial greenhouses or vertical farms.

Furthermore, the approach could be used analogously to detect additional plant species. To implement this, further and more extensive datasets for additional plants need to be created and annotated, as there is a deficit in the agricultural context [174]. Such datasets could also improve the model generalizability of our prototype in terms of detecting various plant varieties through additional training. In addition, the impact of the image quality of training datasets on plant detection performance and accuracy could be examined.

The literature review has shown that there is still a huge demand for research in the field of AR applications for terrestrial greenhouses, but especially for lunar surface greenhouses. We will continue to work on the ARCHIE^2 AR interface to expand its features and improve its practical use. We are planning to conduct a user study for the interface under space analog conditions with different types of plants to evaluate further the effectiveness and performance of the proposed AR technology.

Chapter 6

Extension of the Augmented Reality Interface

Mobile Plant Health Visualizer Based on SI-NDVI Imaging and Augmented Reality Visualization for Space Greenhouses

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Chapter 6 concludes the second part of this thesis and continues to address research questions **RQ3** and **RQ4** through computer science investigations.

This chapter builds upon the AR interface concept presented in Chapter 5. It includes an additional use case for space greenhouse applications, where AR is used to generate and qualitatively visualize plant health information (plant stress) in real-time and in situ. For this purpose, an MPHV based on SI-NDVI imaging has been developed (**C7**).

Using an AR headset, this novel and relatively simple AR visualization approach helps to increase the flexibility and autonomy of OOTs in future space greenhouses from RSTs in MCC. This approach also has the potential to reduce the complexity and cost of the systems required for PHM.

The reported results on the implementation and performance of the MPHV provide essential benchmarks for future studies on terrestrial and space applications (**C7**).

Finally, the benefits and relevance of AR applications in the design and optimization processes of space greenhouses and their operations are presented in this chapter (**C8**).

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6.1 Introduction and Motivation

Food is a vital element in crewed space missions, as it plays a critical role in ensuring the success of the expedition. Space greenhouses have been identified as key elements in meeting the food production requirements for long-duration space missions. [9] However, the reliability and productivity of plant production within greenhouses depend highly on the correct functionality of the utilized technical subsystems. Technical subsystems can become inoperable, and their failure can have a negative impact on plant yield. Additionally, the spread of plant diseases significantly threatens food production in space. Therefore, deploying PHM systems is crucial to detect plant health anomalies early and to prevent plant disease outbreaks [92].

In the context of plant production as part of future space exploration missions, additional constraints affect PHM systems' required utility and efficiency. One of the constraints is the limited availability of expert knowledge and workforce on-site during a mission. To address this challenge, automated image acquisition and remote PHM assessment have been introduced as part of the EDEN ISS project [94]. However, the PHM system utilized on EDEN ISS relied on a static camera system [95] that lacked mobility, leading to an inflexible assessment of the greenhouse plants. Additionally, the extraction of plant health information from the acquired images was conducted remotely, leading to limited autonomy of the operating crew.

Recent research has shown that using AR technology can provide advantageous capabilities to support human operators in various contexts [84, 184], including the space domain [62, 80, 86, 146, 158, 159, 185, 186]. AR technology allows for real-time, context-aware, and hands-free interaction with digital content, enabling operators to visualize and interact with complex datasets in their natural environment [146].

This chapter presents an MPHV based on SI-NDVI imaging and a novel AR plant health visualization approach. The SI-NDVI imaging is performed with a modified GoPro Hero 4 Black camera (GP4), while the image processing is done on a server. The AR plant stress response visualizations are streamed in real-time to a Microsoft HoloLens 2 HMD. To test the performance and functionality of the MPHV, a salinity stress test on tomato plants (*Solanum lysopersicum* cv. 'Nugget') was conducted and evaluated to identify the system limitations and derive an outlook on future research and development.

6.2 Related Work

As mentioned previously, PHM is crucial for future crop production systems to ensure optimal plant growth in space. In the context of human-computer interaction (HCI), various technologies such as AR or ML have already entered the research field of PHM.

As shown in Neto and Cardoso [151], AR used on smartphones can be used in early warning systems for fungal infection detection in terrestrial greenhouses. Another application is insect identification and pest control, displaying the type of insect, pest symptoms, or treatment in AR on mobile devices [152].

AI has also been increasingly used to detect plant diseases in recent years. One example is an application developed by Mohanty *et al.* [187] that can be used on smartphones and uses a deep convolutional neural network to identify 14 crop species and 26 plant diseases. Another application developed by Mathew and Mahesh [188], which uses the YOLOv5 deep learning method, can be used to detect early-stage bacterial spot diseases based on symptoms on bell pepper leaves in terrestrial farms. Additional applications of deep learning techniques for disease diagnosis and management in agriculture can be found in the literature review by Ahmad *et al.* [189].

These applications are designed to provide information to users in the field and support their operational work in real-time. However, using traditional RGB cameras, many applications can only detect plant diseases after the appearance of visual symptoms.

6.2.1 NDVI Imaging

In the 1970s, researchers started space-based remote sensing by launching multispectral imaging instruments aboard satellites to analyze and mitigate droughts. The corresponding data were analyzed using the characteristic spectral response of vegetated surfaces compared to unvegetated. Photosynthetic chlorophyll in healthy vegetation increases its absorption ratio in the visible band of the electromagnetic spectrum and its reflectance ratio in the near-infrared (NIR) band. [190] This relation can be expressed by the Normalized Difference Vegetation Index (NDVI), which relates the reflectance ratios within the electromagnetic NIR and red band [191].

NDVI has become a standard for vegetation monitoring and is now also being used for plant health inspection on a smaller scale, particularly in Controlled Environment Agriculture (CEA) [93]. However, the related acquisition, processing, and analysis of hyperspectral imagery remain a challenging research field as it involves large data volumes, high data dimensionality, and costly hyperspectral instruments [192].

6.2.2 SI-NDVI Imaging

SI-NDVI allows the use of simplified image acquisition and processing by less costly imagers based on modified commercial off-the-shelf RGB cameras. SI-NDVI imaging relates the reflectance ratios within the electromagnetic NIR and blue band, allowing plant stress to be detected before the appearance of visual symptoms. During the image processing, one SI-NDVI value is calculated for each raw image pixel to generate quantitative readings of SI-NDVI histograms and qualitative interpretable false color images (FCIs). In Beisel *et al.* [93], the University of Florida Spectral Imager (UFSI) is presented, which is a heavily modified GP4 using the Back-Bone Ribcage AIR modification kit, providing multiple mechanical mounting points. In addition, the infrared blocking filter of the GP4 was removed, and an NDVI-7 dual bandpass filter allowing light transmission in the ranges 400-575 nm and 675-775 nm and an M12 5.4-mm MP-10 with infrared correction lens was added. [93]

Testing of two UFSIs under space analog conditions inside the EDEN ISS greenhouse in 2018 [95] revealed limitations of the stationary UFSI installation. Due to their fixed mounting, the UFSIs could not be used flexibly from multiple perspectives and simultaneously for all greenhouse plants. To circumvent these limitations, multiple UFSIs or a robotic camera system could be integrated. However, this would increase costs and complexity. Another limitation of the initial deployment resulted from the remote and manual generation of the histograms and FCIs within the science office off-site from the greenhouse. As a result, there was a subsequent delay in providing processed results to the on-site operator, limiting the operational autonomy, even more relevant for future space missions with their telemetry limitations [92].

6.3 Concept

To overcome the limitations of the EDEN ISS PHM approach, a new concept for plant stress visualization using an AR headset and an SI-NDVI imager was developed (Figure 6.1). The plant health visualization process is divided into three steps: (1) raw plant image acquisition, (2) image processing, and (3) false color hologram visualization on the AR headset.

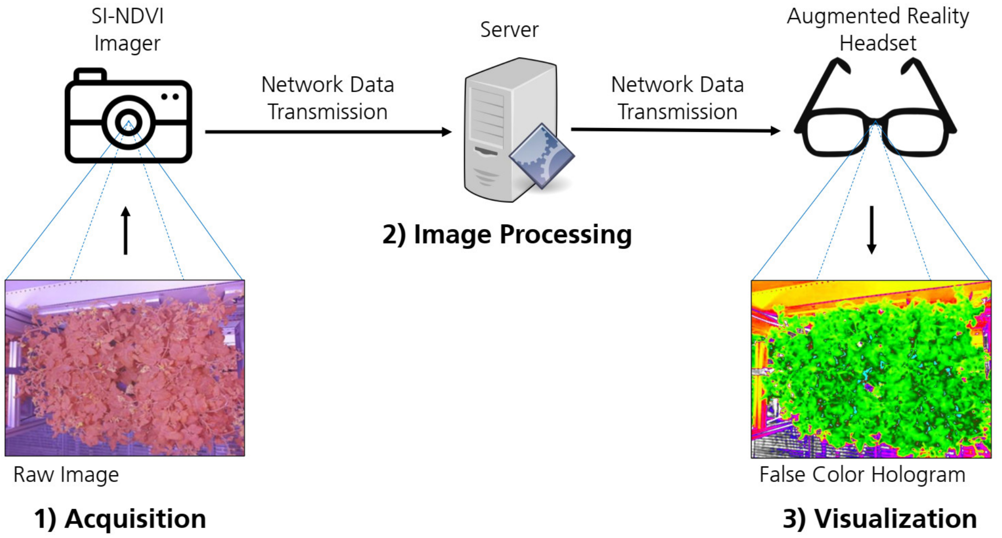

Figure 6.1: Mobile plant health visualization concept that generates false color images based on Single-Image Normalized Difference Vegetation Index (SI-NDVI) calculations and visualizes them as false color holograms on an augmented reality headset.

A camera connected to the AR headset, previously modified by removing the infrared filter in front of the RGB lens and adding a dual wavelengths filter (SI-NDVI filters), captures the raw plant images (step 1). These images are forwarded to a server, and SI-NDVI calculations are performed for each pixel within. Based on the SI-NDVI calculations, the image is converted to an FCI (step 2) and streamed to the AR headset to overlay the user's field of view in the real world with the FCI (step 3). The false colors qualitatively visualize plant stress compared to similar plants or to other plant parts.

The resulting MPHV (Figure 6.2) allows real-time detection and in situ visualization of plant stress. In this context, in situ visualization refers to visualization within the greenhouse on-site in the vicinity of the plants. This increases the user's autonomy by allowing them to easily and quickly locate plant stress, investigate its cause, and having the hands-free to initiate countermeasures with remote support from Earth. In addition, all plants and individual plant parts can be flexibly examined from various perspectives without the need to install additional stationary cameras, reducing investments, space requirements, system weight and complexity, maintenance time, and potential system failures. This makes the system more flexible and easier to integrate into different setups.

6.4 Implementation

Within the following, the implementation of the MPHV is presented from a software and hardware perspective following the work of Kuhr [193].

6.4.1 Hardware

The FCI is visualized as a false color hologram using the HoloLens 2 AR headset. Real-time images are captured (step 1) using a UFSI developed by the University of Florida [93, 95] (Subsection 6.2.2), as the HoloLens 2's built-in infrared and RGB cameras are unsuitable for this application. Furthermore, the UFSI has already been validated for plant stress monitoring under laboratory [93] and space analog conditions [94, 95]. Image processing (step 2) is outsourced to an external server (i7 processor with a CPU clock speed of 4.6 GHz) for optimal computing power and extended battery life of the MPHV. The raw UFSI images are streamed wirelessly to the server for processing, and the false color hologram is streamed wirelessly back to the HoloLens 2 for visualization (step 3). This wireless network requires an additional bridge router as the UFSI provides an access point only. The UFSI camera is mounted onto the HoloLens 2 centrally and in direction of sight to avoid misalignment between the real-time image and the overlaid false color hologram using a 3D-printed mechanism [194] that connects the GoPro's Back-Bone Ribcage AIR modification kit to the HoloLens 2's chunnels (Figure 6.2). The MPHV can be operated for approximately two hours before the UFSI battery is discharged.

Figure 6.2: Mobile plant health visualizer consisting of a University of Florida Spectral Imager (modified GoPro Hero 4 Black) mounted onto a Microsoft HoloLens 2. [193]

6.4.2 Software Development

The developed solution consists of a C# script and a C++ library integrated into a Unity scene, along with the GoPro server and Remote Holographic Player client on the HoloLens 2. The software architecture involves the UFSI streaming raw RGB image frames at 30 FPS, with every fifth frame retrieved for real-time visualization of the FCI without lag. Based on the FCI generation introduced by the University of Florida (Subsection 6.2.2), a C++ functionality is developed to allow real-time FCI generation. This functionality includes raw image pre-processing, calculating an SI-NDVI value for each pixel, and assigning a new color to each pixel according to its SI-NDVI value. The FCI is then copied to the memory that is shared with Unity's runtime, allowing the C# script to apply the color data of the current FCI to a 2D texture container, which is then streamed to the HoloLens 2 for visualization using the Remote Holographic Player application. The three-dimensional position (and hence size) of the displayed two-dimensional hologram is also controlled by the C# script and can be modified within Unity. The Jolly Green Cyan Lookup Table (LUT) [93] is used for intuitive visualization of SI-NDVI values. Healthy vegetation is colored green, with green color saturation increasing with increasing SI-NDVI values. Lower SI-NDVI values are colored yellow, followed by red and purple to represent unhealthy vegetation in decreasing order of SI-NDVI values.

6.5 Evaluation - Salinity Stress Test

A salinity stress test was conducted to investigate the MPHV's capability to detect and visualize plant stress responses.

6.5.1 Setup

Two Orange Cherry tomato (*Solanum lysopersicum* cv. 'Nugget') plants were used for the salinity stress test after approximately 75 days of growth. They were sown on the same date, grew until the salinity stress test under the same conditions in a grow box (200 x 60 x 40 cm) with white walls (Figure 6.3), and were vegetatively healthy. The tomato plants were illuminated during the first three weeks for 16 h day^{-1} and after that for 12 h day^{-1} by a 6-band multispectral spLED GmbH BloomPower black180 (390 nm - 1.68%; 460 nm - 8.40%; 612 nm - 8.40%; 660 nm - 78.15%; 730 nm - 1.68%; 6400 K - 1.68%) with a photosynthetic photon flux density (PPFD) of 600 µmol m^{-2} s^{-1} at a distance of 35 cm. The distance between the LED grow light and the tomato plant canopies was approximately 50 cm.

Figure 6.3: Setup of the salinity stress test with two tomato plants under LED grow light in the grow box before salt treatment (left); The orange arrows show the leaves of the stressed tomato plant and the light blue arrows show the leaves of the control tomato plant examined for the salt treatment (right). Reproduced and modified from Kuhr [193].

6.5.2 Procedure

For the salinity stress test, the MPHV was set to operational mode and spatial calibration of the system was performed. The two tomato plants were examined in the grow box under the LED grow light. The MPHV was worn throughout the salinity stress test by a 1.90 m person. The entire salinity stress test was recorded by the HoloLens 2.

In a first step, using the MPHV, three leaves of each tomato plant were examined at three different heights (top, middle, bottom) from two perspectives, i.e., the side-view and the top-view, and at a distance of approximately 50 cm to obtain a baseline for later comparison. This reduced the potential angle influence on the calculated false color hologram colors on the MPHV. Leaves were selected on a sample basis for the entire plant. Since the MPHV is a mobile application for plant stress detection, no fixed mounting of the MPHV was intended.

In a second step, one of the two tomato plants, hereinafter referred to as the stressed tomato plant, was treated once with 400 ml of a 3% sodium chloride solution (Figure 6.3). The other tomato plant was the control tomato plant and received no salt treatment. Two hours after the salt treatment, the same leaves of the two tomato plants were examined using the MPHV from the same distance, perspectives, and angles to allow comparison with the images from the first step.

6.5.3 Results

Two hours after the salt treatment, no difference was visible to the human eye between the stressed tomato plant before and after the treatment. The same applied to the control tomato plant. However, in the area of all examined leaves of the stressed tomato plant, significant color changes from green to yellow/red/purple, from yellow to red/purple, or from red to purple between the superimposed false color hologram before and after the salt treatment could be detected with the help of the MPHV. This could be observed both in the top-view and, although not as clearly, in the side-view perspective (Figure 6.4). The shift to colors associated with lower SI-NDVI values could be an indication of plant stress due to the salt treatment.

No changes in false color hologram colorization and associated measured SI-NDVI values were detected during the salinity stress test for any of the control tomato plant leaves examined with the MPHV from both perspectives. Thus, no false positive plant stress detection was experienced.

These results show that it was possible to correctly detect plant stress with the MPHV even before any change in the stressed tomato plant was visible to the human eye. Ten hours after the salt treatment, the stressed tomato plant lost stability and collapsed. During the entire salinity stress test, the stems of both tomato plants were visualized unchanged in dark green color on the false color hologram.

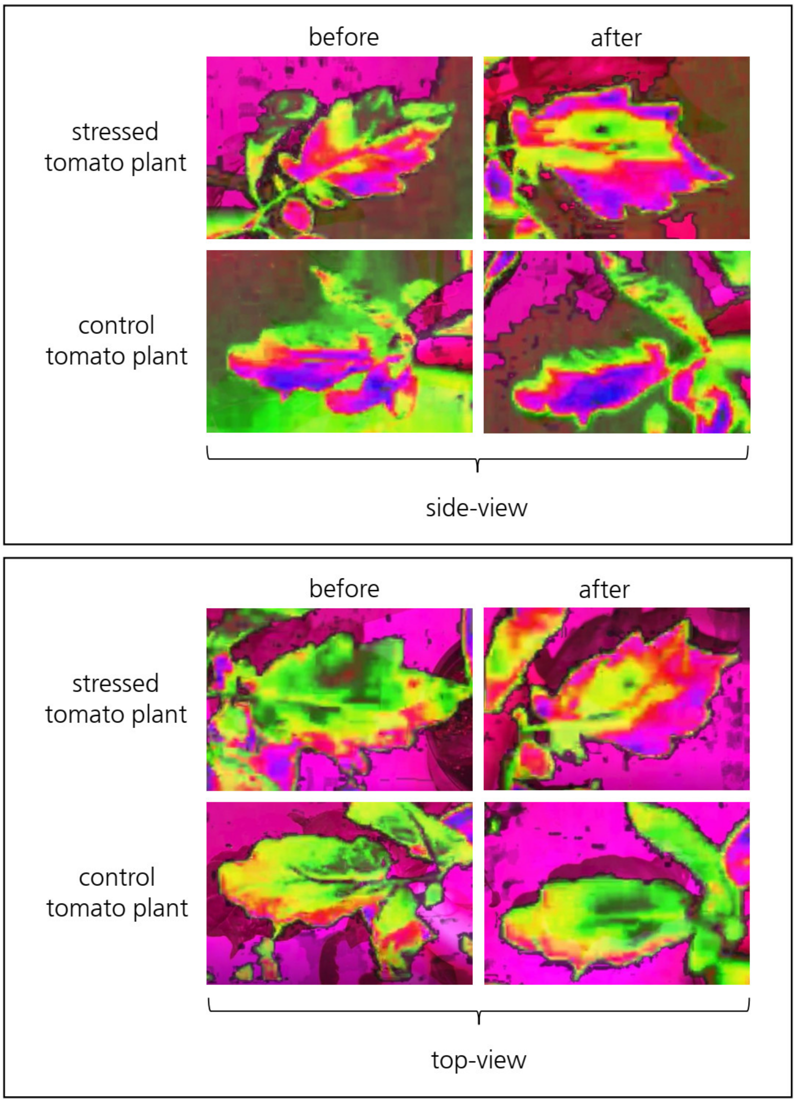

Figure 6.4: Exemplary video stream screenshots of the mobile plant health visualizer user perspective (using the Jolly Green Cyan Look Up Table) during the salinity stress test. Side-view of middle level leaves before and after the salt treatment for a stressed and control tomato plant (top). Top-view of middle level leaves before and after the salt treatment for a stressed and control tomato plant (bottom).

6.6 Discussion

6.6.1 Server Approach

The deployment of the software code to the server instead of the HoloLens 2 leads to multiple advantages and disadvantages. The deployment method was chosen to prevent processing performance issues caused by the lower computing power of the HoloLens 2, affecting the fluent display of the false color hologram.

Measurements showed that the implemented solution enabled image processing at a frame rate of 7 FPS. The wireless connection of the UFSI, server, and HoloLens 2 during the use of the MPHV was not a limiting performance factor regarding fluent visualization, with network traffic measurements of approximately 12%. With the UFSI streaming raw images at 30 FPS, the image processing could be identified as the significant limitation to the fluent visualization of the false color hologram. However, the tests showed that the image processing frame rate of 7 FPS was still sufficient for the respective application.

Although the tests presented in this chapter identified the UFSI's battery life as the limiting factor of the operation time, outsourcing the processing from the HoloLens 2 could prove beneficial to the available battery life and allow for longer operation time. Using less of the HoloLens 2 processing power also allows to start additional applications in parallel onboard the HoloLens 2.

However, one major disadvantage of this solution is that some inputs to control the visualization of the FCI, such as launching the visualization, spatial calibration, or changing settings, cannot be made without using Unity on the server.

6.6.2 SI-NDVI Range Selection

In the current MPHV prototype, the non-vegetative objects visible on the false color hologram are colored based on low SI-NDVI values using the Jolly Green Cyan LUT. An SI-NDVI value below zero is considered to represent non-vegetative elements on an SI-NDVI image. To achieve an even better visual separation of the tomato plants from their surroundings on the false color hologram, the pixels with SI-NDVI values below a certain threshold, such as zero, could be displayed fully transparent to color only the plant material. For this purpose, the alpha value controlling the transparency of these pixels would be set to zero. In order to achieve a clear separation and at the same time correctly represent plant stress, a compromise must be made when setting the SI-NDVI threshold value, because if the threshold value is chosen too low, stressed plant parts could also be falsely displayed transparent instead of in the reddish spectrum. To determine the optimal SI-NDVI threshold value, further research needs to be conducted.

6.6.3 Plant Stress Detection

During the salinity stress test, two limitations of the MPHV were identified regarding plant stress detection. The first limitation represents the dependence of the false color hologram colorization on the angle between the observed leaf and the MPHV (observation angle), with a constant angle between observed leaf and light source (LED grow light).

The second limitation is the dependence of the false color hologram colorization on the angle between the light source and the observed leaf, with a constant angle between observed leaf and MPHV. As already mentioned in Subsection 6.5.3, plant stress was not as clearly detectable in the side-view as in the top-view perspective. Thus, on the false color hologram in the side-view of the control plant, the upper leaf areas tended to be colored in colors corresponding to high SI-NDVI values and the lower leaf areas tended to be colored in colors corresponding to lower SI-NDVI values (Figure 6.4). A reason for this could be based on the higher illumination exposure from the LED grow light of the upper leaf areas compared to the lower leaf areas.

Due to these limitations, plant stress detection is more practical in the top-view rather than the side-view. Mishra *et al.* [192] also reported difficulties due to illumination effects in hyperspectral imaging at close range and stated that "there is still no standard method to deal with these illumination effects". Further tests with a static fixation of the MPHV and the object to be observed should be conducted to investigate the illumination effects on the stress monitoring capabilities of the MPHV.

Besides this, the conducted tests included only Orange Cherry tomato plants, as this plant species was already used in the initial validation of the SI-NDVI method [95]. Further tests need to show whether the MPHV could be used on other plant species, whether the Jolly Green Cyan LUT provides plausible plant health information within the visualized false color hologram, or whether it needs to be adapted.

6.7 Conclusion and Outlook

In this chapter, a mobile AR application was presented to detect and visualize in situ and real-time plant stress responses qualitatively, even before the appearance of visual symptoms. The presented MPHV consists of a UFSI (a modified GP4) to conduct SI-NDVI imaging and a HoloLens 2 visualizing the SI-NDVI values in AR. The UFSI is mounted onto the HoloLens 2 using a 3D-printed mounting mechanism and connected to it via a wireless network. A salinity stress test with two tomato plants demonstrated sufficient technical functionality and performance of the MPHV in detecting and visualizing plant stress.

Current SI-NDVI imaging methods require either multiple stationary imagers or expensive robotic systems. Due to the relatively simple MPHV, the complexity and costs of such systems could be reduced. The MPHV aims to support on-site operators with mobile and in situ plant health assessment capabilities, increasing their autonomy from RSTs on Earth. Moreover, the MPHV enables close-up inspection of specific plant parts from different perspectives, and the plants can be inspected anywhere in the cultivation area.

In future work, the MPHV should be improved and the limitations mentioned above should be further investigated. These include the angular dependence of the AR hologram colorization on the angle of observation and the angle of illumination. Attaching a small LED grow light to the MPHV could ensure a constant illumination angle and thus represent a promising approach to eliminate the respective limitations. The ability of the MPHV to detect other causes of stress, such as light stress, also with focus on stress in other plant species will be investigated. Potential improvements to the MPHV could be achieved by adding gesture control and deploying the entire

AR application on the HoloLens 2 or on future AR headsets with higher computing power to provide even more flexible operations.

In conclusion, the proposed MPHV provides promising insights into a novel, relatively simple, and effective approach to PHM in space greenhouses and on Earth. By utilizing AR technology, the system provides a more flexible and interactive assessment of plant health, allowing for increased autonomy of on-site operators. Furthermore, the proposed MPHV could be applied to other CEA applications, making the system relevant and applicable beyond space exploration missions. The development and implementation of such systems demonstrate the significance of HCI in designing and optimizing technologies used in space missions.

Chapter 7

Overall Conclusion

Chapter 7 concludes the thesis by outlining each chapter's key contributions (**C1** to **C8**). This is followed by an outline of the planned future work, with an indication of the expected results and implications. Finally, a list of research gaps is presented.

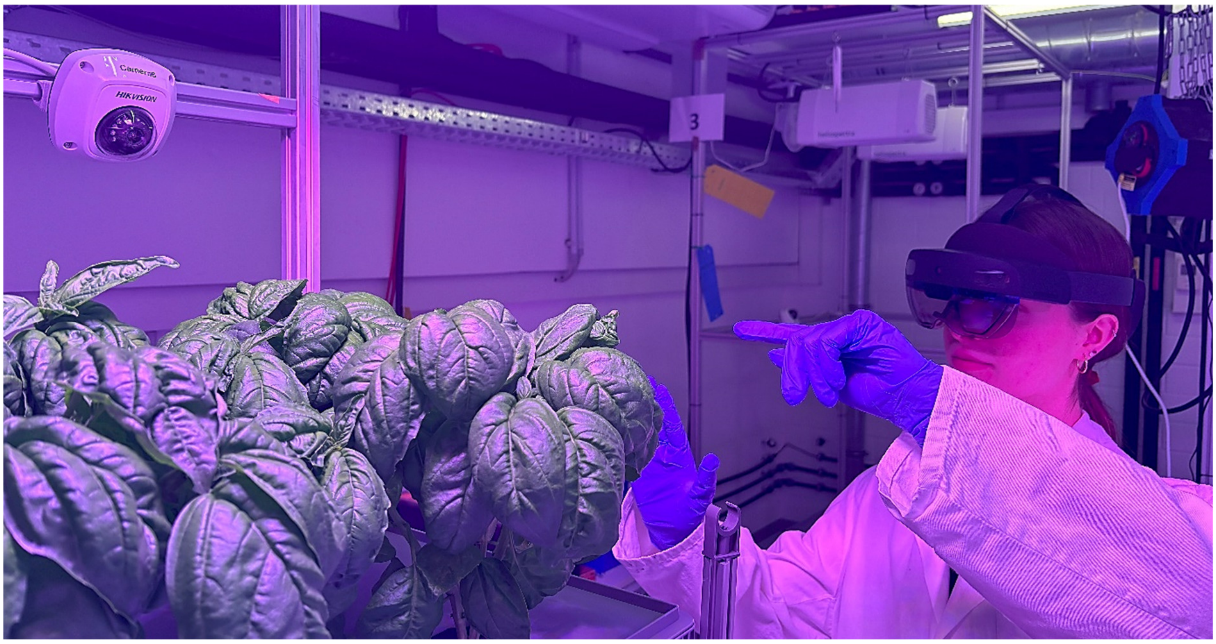

Figure 7.1: A researcher wearing an augmented reality headset looks at plants cultivated under controlled environmental conditions in the Space Habitation Plant Laboratory at the Institute of Space Systems of the German Aerospace Center in Bremen.

7.1 Key Contributions

In this thesis, an interdisciplinary approach was chosen to solve challenges in space research by implementing computer science (Figure 1.3). The first part of the thesis was divided into three chapters focusing on space-related research investigations related to the research questions **RQ1** and **RQ2**.

To address these research questions, crew time measurements of plant cultivation systems in various space analog facilities and plant experiment hardware on the ISS were analyzed and compared in Chapter 2. The limited crew time data available was expanded (**C1**), and a standardized methodology for measuring on-site greenhouse operators' crew time was developed to facilitate comparability of crew time data and its analysis (**C4**). Furthermore, the factors influencing crew time in space mission scenarios with greenhouses were investigated, and the differences were evaluated (**C2**).

In Chapter 3, the investigations of crew time for space greenhouse operations from Chapter 2 were further elaborated and extended to include more detailed crew time data for RSTs in the MCC (**C1**). The extended crew time database resulted in the development of a standardized methodology for measuring crew time of greenhouse RSTs to facilitate the evaluation and comparability of crew time datasets (**C4**). In addition to the crew time, the workload of space analog greenhouse operators (remote and on-site) was examined to better understand the operations of future planetary surface greenhouses (**C1**).

In Chapter 4, the workload value database for the operations of space greenhouses from Chapter 3 was expanded, and workload measurements on a daily, weekly, and monthly basis, as well as for recurring tasks, were investigated in more detail (**C1**). Furthermore, recommendations were made on which recurring greenhouse tasks/procedures should be facilitated, automated, or more remotely controlled to optimize operations in future planetary surface greenhouses (**C3**).

The investigations of the first part of this thesis have demonstrated that the crew time for space missions is a limited and valuable resource. In addition, it was shown that crew time and the related overall workload for space greenhouses need to be optimized for efficient mission planning and implementation. Detailed analysis determined which workload dimensions, depending on the various groups involved in planetary surface greenhouse operations, have the most significant impact on the overall workload and how the workload levels change throughout a mission. Furthermore, the presented data demonstrated that the crew time and workload of the RSTs should also be addressed in the design and operations of space greenhouses, as they represent a significant share of the total crew time and workload.

The investigation of research questions **RQ1** and **RQ2** in the first chapters of this thesis led to the creation of **RQ3** and **RQ4**, which were explored in the chapters of the second part of this thesis. These chapters focused on computer science-related investigations to optimize workload and crew time for space greenhouses.

Chapter 5 presented a concept for an AR interface called ARCHIE^2 that was developed to address **RQ3** and **RQ4** (**C5**). The AR interface investigations demonstrated its potential to reduce the workload and crew time by facilitating the tasks of all groups involved in space greenhouse operations. The results of the implementation and performance investigations of a new tool for real-time plant detection and augmentation with plant-specific information as part of the ARCHIE^2 AR interface were also presented (**C6**).

In Chapter 6, another use case for AR related to space greenhouse operations, including implementation and performance results, was presented. The MPHV developed for this purpose uses an AR headset to generate and qualitatively visualize information on plant health (plant stress) in real-time and in situ (**C7**). This new and relatively simple approach helps to increase the autonomy and flexibility of space greenhouse on-site operators while reducing the complexity and cost of the PHM systems used.

The results of Chapters 5 and 6 provide important benchmarks for future studies and extend the limited research in AR applications for space greenhouses (**C5**, **C6**, **C7**). In addition, the relevance and benefits of AR applications for optimizing the design and operations of space greenhouses were demonstrated (**C8**).

7.2 Future Work and Research Gaps

In future work, it is planned to extend the functionality of the ARCHIE^2 AR interface and further optimize its usability. A multi-participant user study is planned to be conducted at a space analog test site such as Antarctica to test the AR interface under space analog conditions. Two participant groups will perform various tasks in a space analog greenhouse over a whole analog mission with and without using the AR interface. This direct comparison between scenarios will help provide more detailed recommendations for the use of AR applications in space greenhouses. During the user study, crew time and workload will be measured and compared to the values presented in the databases of this thesis to substantiate the recommendations for using AR to optimize space greenhouse workflows.

In addition to the NASA TLX questionnaire, other evaluation methods could be used to assess the ARCHIE^2 AR interface, such as the System Usability Scale (SUS) questionnaire [195, 196], which focuses on assessments of system usability, or the Technology Acceptance Model for Augmented Reality and Wearable Technologies (TAMARA) questionnaire [166, 197, 198] to evaluate the user's technology acceptance for an AR system. The user study will also investigate what inference times and frame rates are required to ensure a satisfactory user experience regarding performance and overall practical use of plant detection in space greenhouses. Further studies will investigate which space greenhouse tasks should still be performed manually and to what extent, depending on the complexity of the automation and the benefits for the psychological well-being of the on-site operators.

The preparation of analog missions requires long planning periods, as evident in the case of NM III, with mission durations of up to 14 months and supplies delivered to NM III once a year [199]. Since the AR system would have to be shipped to NM III and the organization of the user study would have to be completed several months before the actual execution, it was not possible to perform such a mission within the limited scope of this thesis. Based on our current research and the previously mentioned benefits of AR, the user study under space analog conditions is expected to confirm that crew time and workload can be reduced in an AR scenario compared to a non-AR scenario. The AR scenario is expected to be characterized by greater autonomy of the on-site operators from the RSTs in the MCC, better guidance, and more efficient/accurate task execution with fewer errors and associated delays. The on-site operators' field of view could be shared with the RSTs, and annotations created by both operator groups could be visualized in the on-site operators' AR environment. This approach could facilitate and improve the RSTs' ability to provide nominal and non-nominal support, as the RSTs could better understand the specific situation on-site. Visualization of all relevant data, procedures, timelines, video examples, or interactive checklists could increase confidence in the positive outcome of task completion and reduce the on-site operators' pressure to perform by providing immediate feedback.

To improve the MPHV's functionality, an LED spotlight that ensures a constant illumination angle is planned to be added, reducing the system's dependence on illumination and observation angles. The system will be expanded to include the detection of plant stress for additional plant species and plant stressors. The visual differentiation of plants from their surroundings in the AR environment will also be improved. The MPHV is an active area of research and development that will require years of further optimization, although initial applications are promising.

To extend the capability of the ARCHIE^2 plant detection module to detect additional plant species using the methods described in this thesis, more annotated plant image datasets of additional plant species are required, as this represents a research gap in the agricultural context [174]. These datasets should include images of improved quality and contain a high number of images (approximately 1,500 images per class) with more than 10,000 instances (labeled objects) per class [181]. Images should be taken at different stages of plant growth, with different camera devices, and from various perspectives and distances to cover all possible variations that may occur when working in the greenhouse [181].

Improved quality of plant image datasets would also benefit automated plant cultivation systems using robotics and AI. High-quality datasets could be used to train deep learning models to detect specific plant parts in addition to whole plants. This capability would enable specialized plant-tending robots to automatically perform pre-defined tasks such as pruning, pollination, or harvesting at the optimal time. Based on the more detailed information, predictions about the optimal harvesting time and the expected yield could be made. These predictions are essential for future space greenhouse operations. They could be used for automated crop planning tools, which could also be visualized on AR headsets. Furthermore, more detailed procedures could be visualized on the AR headset for manual tasks, providing visual information on the specific areas of a particular plant that need to be tended rather than just providing textual descriptions. For a robot-assisted greenhouse, the ARCHIE^2 AR interface could be extended to include a submenu for the robotic environment, allowing the greenhouse on-site operators to interact with the robotic system. [200]

Other research gaps identified in this thesis include the need for additional detailed crew time and workload values for space greenhouse operations. Values are required for specific tasks and off-nominal events, such as repairs, or for crew time in relation to crop nutritional content. These values are essential for planning and designing future planetary surface greenhouses, including selecting plants for various mission scenarios. Further research is also needed to improve evaluation capabilities to assess what workload levels might be perceived as acceptable in specific contexts and how these values relate to operator performance [141].

While AR headsets have been demonstrated to be a valuable addition to space greenhouse operations, there is still an immense need for research on AR applications for use in greenhouses, in space and on Earth. In addition to the previously mentioned research gaps to be investigated during the planned user study, there are challenges associated with existing AR headset hardware [63, 201]. For example, the form factor of current AR headsets can still be improved, as they are too large, too heavy [201], and therefore often too uncomfortable [63] to be used for extended periods. Their power consumption [63] needs to be reduced to ensure long-term use, given the short battery life. Another critical issue is the processing power [63, 201] and speed of AR headsets, which currently makes it challenging to run computationally intensive applications such as plant detection or NDVI calculations directly on the AR headset. Finally, current AR headsets still have a limited field of view for the user [63, 201].

However, the technological development of AR has progressed rapidly in recent years [63]. According to Moore's Law [202], the functionality and performance of digital electronics, such as mobile processors, double periodically for a given power consumption, area, and price [203]. Although the doubling intervals are getting longer and the end of Moore's law for semiconductors seems imminent, new technologies such as improved computational architectures or three-dimensional chip design could allow for further improvements in processor performance and a continuation of Moore's Law [203]. Accordingly, more powerful AR headsets could solve some of the hardware challenges mentioned previously.

The data and results presented in this thesis regarding workload, crew time, and use of AR applications are of significant importance for planning future space missions and designing space greenhouses to ensure reliable/efficient operations and related mission success. The results are also relevant to today's terrestrial food production systems and could find suitable applications in greenhouses or vertical farms on Earth [204].

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References

[1] L. Poulet, C. Zeidler, J. Bunchek, P. Zabel, V. Vrakking, D. Schubert, G. Massa, and R. Wheeler, "Crew time in a space greenhouse using data from analog missions and Veggie," *Life Sciences in Space Research*, vol. 31, pp. 101–112, 2021, doi: 10.1016/j.lssr.2021.08.002.

[2] C. Zeidler, G. Woeckner, J. Schöning, V. Vrakking, P. Zabel, M. Dorn, D. Schubert, B. Steckelberg, and J. Stakemann, "Crew time and workload in the EDEN ISS greenhouse in Antarctica," *Life Sciences in Space Research*, vol. 31, pp. 131–149, 2021, doi: 10.1016/j.lssr.2021.06.003.

[3] C. Zeidler and J. Bunchek, "Workload measurements in the EDEN ISS greenhouse during the 2021 Antarctic overwintering mission," *52nd International Conference on Environmental Systems, 16-20 July 2023, Calgary, Alberta, Canada*, 2023.

[4] C. Zeidler, M. Klug, G. Woeckner, U. Clausen, and J. Schöning, "ARCHIE^2: An augmented reality interface with plant detection for future planetary surface greenhouses," in *2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, Sydney, Australia, 2023, pp. 601–610.

[5] C. Zeidler, L. Kuhr, J. B. Callaham, and J. Schöning, "Mobile plant health visualizer based on SI-NDVI imaging and augmented reality visualization for space greenhouses," *SpaceCHI 3.0: A Conference on Human-Computer Interaction for Space Exploration, 22-23 June 2023 at MIT Media Lab*, 2023.

[6] ISECG, "The Global Exploration Roadmap," NP-2018-01-2502-HQ, Jan. 2018.

[7] NASA, "Moon to Mars Architecture Definition Document (ESDMD-001) – Revision A – Management Directive 01," ESDMD-001 Rev-A MD-01, Mar. 2024.

[8] ISECG, "Global Exploration Roadmap - Supplement October 2022: Lunar surface exploration scenario update," NP-2022-09-3075-HQ, Oct. 2022.

[9] G. L. Douglas, R. M. Wheeler, and R. F. Fritsche, "Sustaining astronauts: Resource limitations, technology needs, and parallels between spaceflight food systems and those on Earth," *Sustainability*, vol. 13, no. 16, p. 9424, 2021, doi: 10.3390/su13169424.

[10] R. M. Wheeler, "Plants for human life support in space: From Myers to Mars," *Gravitational and Space Biology*, vol. 23, no. 2, pp. 25–36, 2010.

[11] S. Bates, V. Gushin, G. Bingham, A. Vinokhodova, J. Marquit, and V. Sychev, "Plants as countermeasures: A review of the literature and application to habitation systems for humans living in isolated or extreme environments," *Habitation*, vol. 12, no. 1, pp. 33–40, 2009, doi: 10.3727/154296610X12686999887201.

[12] S. Ulamec, J. Biele, and E. Trollope, "How to survive a Lunar night," *Planetary and Space Science*, vol. 58, 14-15, pp. 1985–1995, 2010, doi: 10.1016/j.pss.2010.09.024.

[13] V. Maiwald, "Being Selene's guest: Analysis of the lunar environment and its impact on base location selection," *64th International Astronautical Congress 2013, 23-27 September 2013, Beijing, China*, 2013.

[14] S. Häuplik-Meusburger, C. Paterson, D. Schubert, and P. Zabel, "Greenhouses and their humanizing synergies," *Acta Astronautica*, vol. 96, pp. 138–150, 2014, doi: 10.1016/j.actaastro.2013.11.031.

[15] NASA, *Station science 101: Plant research - NASA.* [Online]. Available: https://www.nasa.gov/missions/station/ways-the-international-space-station-helps-us-study-plant-growth-in-space/ (accessed: Feb. 22 2024).

[16] D. Schubert, "System Analysis of Plant Production in Greenhouse Modules as an Integrated Part of Planetary Habitats," Dissertation, Fachbereich Produktionstechnik, Universität Bremen, Bremen, 2017.

[17] F. Foucher, K. Hickman-Lewis, A. Hutzler, K. H. Joy, L. Folco, J. C. Bridges, P. Wozniakiewicz, J. Martínez-Frías, V. Debaille, M. Zolensky, H. Yano, N. Bost, L. Ferrière, M. Lee, J. Michalski, H. Schroeven-Deceuninck, G. Kminek, M. Viso, S. Russell, C. Smith, J. Zipfel, and F. Westall, "Definition and use of functional analogues in planetary exploration," *Planetary and Space Science*, vol. 197, p. 105162, 2021, doi: 10.1016/j.pss.2021.105162.

[18] M. Bamsey, P. Zabel, C. Zeidler, L. Poulet, D. Schubert, E. Kohlberg, and T. Graham, "Design of a containerized greenhouse module for deployment to the Neumayer III Antarctic Station," *44th International Conference on Environmental Systems, 13-17 July 2014, Tucson, Arizona, USA*, 2014.

[19] W. B. Garry and J. E. Bleacher, *Analogs for planetary exploration*: Geological Society of America, 2011.

[20] L. Poulet and O. Doule, "Greenhouse automation, illumination and expansion study for mars desert research station," *65th International Astronautical Congress 2014, Sep-Oct 2014, Toronto, Canada*, 2014. [Online]. Available: https://elib.dlr.de/94134/

[21] B. H. Foing, C. Stoker, and P. Ehrenfreund, "Astrobiology field research in Moon/Mars analogue environments," *International Journal of Astrobiology*, vol. 10, no. 3, pp. 137–139, 2011, doi: 10.1017/S1473550411000139.

[22] D. Eppler, B. Adams, D. Archer, G. Baiden, A. Brown, W. Carey, B. Cohen, C. Condit, C. Evans, C. Fortezzo, B. Garry, T. Graff, J. Gruener, J. Heldmann, K. Hodges, F. Hörz, J. Hurtado, B. Hynek, P. Isaacson, C. Juranek, K. Klaus, D. Kring, N. Lanza, S. Lederer, G. Lofgren, M. Marinova, L. May, J. Meyer, D. Ming, B. Monteleone, C. Morisset, S. Noble, E. Rampe, J. Rice, J. Schutt, J. Skinner, C. M. Tewksbury-Christle, B. J. Tewksbury, A. Vaughan, A. Yingst, and K. Young, "Desert Research and Technology Studies (DRATS) 2010 science operations: Operational approaches and lessons learned for managing science during human planetary surface missions," *Acta Astronautica*, vol. 90, no. 2, pp. 224–241, 2013, doi: 10.1016/j.actaastro.2012.03.009.

[23] L. Poulet, G. D. Massa, R. Wheeler, T. Gill, R. Morrow, C. Steele, T. Swarmer, K. Binsted, and J. Hunter, "Demonstration test of electrical lighting systems for plant growth in HI-SEAS analog mars habitat," *65th International Astronautical Congress 2014, Sep-Oct 2014, Toronto, Canada*, 2014. [Online]. Available: https://elib.dlr.de/94135/

[24] S. Häuplik-Meusburger, K. Binsted, and T. Bassingthwaighte, "Habitability studies and full scale simulation research: Preliminary themes following HISEAS mission IV," *47th International Conference on Environmental Systems, 16-20 July 2017, Charleston, South Carolina, USA*, 2017.

[25] NASA, *Using a 'Cave Rover,' NASA learns to search for life underground.* [Online]. Available: https://www.nasa.gov/universe/using-a-cave-rover-nasa-learns-to-search-for-life-underground/ (accessed: Oct. 11 2023).

[26] M. von Ehrenfried, *From cave man to cave Martian*. Cham: Springer International Publishing, 2019.

[27] B. Todd and M. Reagan, "The NEEMO project: A report on how NASA utilizes the "Aquarius" undersea habitat as an analog for long-duration space flight," in *Engineering, construction, and operations in challenging environments*, League City, Houston, Texas, United States, 2004, pp. 751–758.

[28] E. Feichtinger, R. Charles, D. Urbina, P. Sundblad, C. Fuglesang, and M. Zell, "Mars-500 – A testbed for psychological crew support during future human exploration missions," in *2012 IEEE Aerospace Conference*, Big Sky, MT, 2012, pp. 1–17.

[29] Y. Fu, L. Li, B. Xie, C. Dong, M. Wang, B. Jia, L. Shao, Y. Dong, S. Deng, H. Liu, G. Liu, B. Liu, D. Hu, and H. Liu, "How to establish a bioregenerative life support system for long-term crewed missions to the Moon or Mars," *Astrobiology*, vol. 16, no. 12, pp. 925–936, 2016, doi: 10.1089/ast.2016.1477.

[30] F. B. Salisbury, J. I. Gitelson, and G. M. Lisovsky, "Bios-3: Siberian experiments in bioregenerative life support," *BioScience*, vol. 47, no. 9, pp. 575–585, 1997, doi: 10.2307/1313164.

[31] I. I. Gitelson, I. A. Terskov, B. G. Kovrov, G. M. Lisovskii, Y. Okladnikov, F. Sid'ko, I. N. Trubachev, M. P. Shilenko, S. S. Alekseev, I. M. Pan'kova, and L. S. Tirranen, "Long-term experiments on man's stay in biological life-support system," *Advances in Space Research*, vol. 9, no. 8, pp. 65–71, 1989, doi: 10.1016/0273-1177(89)90030-6.

[32] M. Bamsey, A. Berinstain, T. Graham, P. Neron, R. Giroux, S. Braham, R. Ferl, A.-L. Paul, and M. Dixon, "Developing strategies for automated remote plant production systems: Environmental control and monitoring of the Arthur Clarke Mars Greenhouse in the Canadian High Arctic," *Advances in Space Research*, vol. 44, no. 12, pp. 1367–1381, 2009, doi: 10.1016/j.asr.2009.08.012.

[33] R. L. Patterson, G. A. Giacomelli, M. Kacira, P. D. Sadler, and R. M. Wheeler, "Description, operation and production of the South Pole Food Growth Chamber," *Acta Hortic.*, no. 952, pp. 589–596, 2012, doi: 10.17660/ActaHortic.2012.952.75.

[34] D. Schubert, M. Bamsey, P. Zabel, C. Zeidler, and V. Vrakking, "Status of the EDEN ISS greenhouse after on-site installation in Antarctica," *48th International Conference on Environmental Systems, 8-12 July 2018, Albuquerque, New Mexico, USA*, 2018.

[35] V. Vrakking, C. Zeidler, P. Zabel, M. Dorn, and D. Schubert, "Status and future of the EDEN ISS Mobile Test Facility," *International Conference on Environmental Systems*, 2020.

[36] H. Gernandt, El Naggar, S. E. D., J. Janneck, T. Matz, and C. Drücker, "From Georg Forster Station to Neumayer Station III - a sustainable replacement at Atka bay for future," *Polarforschung, Bremerhaven, Alfred Wegener Institute for Polar and Marine Research & German Society of Polar Research*, vol. 76, 1/2, pp. 59–85, 2007.

[37] C. Wesche, R. Weller, G. König-Langlo, T. Fromm, A. Eckstaller, U. Nixdorf, and E. Kohlberg, "Neumayer III and Kohnen Station in Antarctica operated by the Alfred Wegener Institute," *Journal of large-scale research facilities JLSRF*, vol. 2, 2016, doi: 10.17815/jlsrf-2-152.

[38] P. Zabel, C. Zeidler, V. Vrakking, M. Dorn, and D. Schubert, "Biomass production of the EDEN ISS space greenhouse in Antarctica during the 2018 experiment phase," *Frontiers in Plant Science*, vol. 11, p. 656, 2020a, doi: 10.3389/fpls.2020.00656.

[39] V. Vrakking, D. Schubert, P. Zabel, C. Zeidler, M. Dorn, R. Ferl, and A.-L. Paul, "EDEN ISS – Greenhouse in Antarctica," in vol. 758, *Expeditions to Antarctica: ANT-Land 2020/21 Neumayer Station III, Kohnen Station, Flight Operations and Field Campaigns*, T. Fromm, C. Oberdieck, T. Heitland, and C. Wesche, Eds., 2021, pp. 59–66.

[40] National Research Council, *Factors affecting the utilization of the International Space Station for research in the biological and physical sciences*. Washington, D.C.: National Academies Press, 2003.

[41] C. Stromgren, F. Escobar, S. Rivadeneira, W. Cirillo, and K. E. Goodliff, "Predicting crew time allocations for lunar orbital missions based on historical ISS operational activities," in *2018 AIAA SPACE and Astronautics Forum and Exposition*, Orlando, FL, 2018.

[42] NASA, *Commercial and marketing pricing policy.* [Online]. Available: https://www.nasa.gov/leo-economy/commercial-use/pricing-policy (accessed: Jun. 25 2023).

[43] J. Marquez, S. Hillenius, M. Healy, and J. Silva-Martinez, "Lessons learned from International Space Station crew autonomous scheduling test," *International Workshop on Planning and Scheduling for Space (IWPSS)*, 2019.

[44] E. Coleshill, L. Oshinowo, R. Rembala, B. Bina, D. Rey, and S. Sindelar, "Dextre: Improving maintenance operations on the International Space Station," *Acta Astronautica*, vol. 64, 9-10, pp. 869–874, 2009, doi: 10.1016/j.actaastro.2008.11.011.

[45] J. F. Russell, D. M. Klaus, and T. J. Mosher, "Applying analysis of International Space Station crew-time utilization to mission design," *Journal of Spacecraft and Rockets*, vol. 43, no. 1, pp. 130–136, 2006, doi: 10.2514/1.16135.

[46] B. Mattfeld, C. Stromgren, H. Shyface, W. Cirillo, and K. Goodliff, "Developing a crew time model for human exploration missions to Mars," in *2015 IEEE Aerospace Conference*, Big Sky, MT, 2015, pp. 1–17.

[47] P. Eckart, *Spaceflight life support and biospherics*. Dordrecht: Springer Netherlands, 1996.

[48] P. Zabel, C. Zeidler, V. Vrakking, M. Dorn, and D. Schubert, "Crewtime in a space greenhouse based on the operation of the EDEN ISS greenhouse in Antarctica," *49th International Conference on Environmental Systems, 7-11 July 2019, Boston, Massachusetts, USA*, 2019b.

[49] P. Milgram and F. Kishino, "A Taxonomy of Mixed Reality Visual Displays: IEICE Trans. Information Systems. vol. E77-D, no. 12. 1321-1329.," *IEICE Trans. Information Systems*, E77-D, no. 12, 1321–1329, 1994.

[50] R. T. Azuma, "A Survey of Augmented Reality," *Presence: Teleoperators and Virtual Environments*, vol. 6, no. 4, pp. 355–385, 1997, doi: 10.1162/pres.1997.6.4.355.

[51] M. Tönnis, *Augmented Reality: Einblicke in die Erweiterte Realität*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010.

[52] J. Peddie, *Augmented Reality*. Cham: Springer International Publishing, 2017.

[53] NASA ARC, "NASA Task Load Index (TLX): Volume 1.0 - Paper and Pencil Package," 1986.

[54] S. G. Hart and L. E. Staveland, "Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research," in *Advances in Psychology, Human mental workload*: Elsevier, 1988, pp. 139–183.

[55] S. G. Hart, "Nasa-Task Load Index (NASA-TLX); 20 years later," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 50, no. 9, pp. 904–908, 2006, doi: 10.1177/154193120605000909.

[56] E. A. Bustamante and R. D. Spain, "Measurement invariance of the Nasa TLX," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 52, no. 19, pp. 1522–1526, 2008, doi: 10.1177/154193120805201946.

[57] P. Zabel, M. Bamsey, C. Zeidler, V. Vrakking, and B.-W. e. a. Johannes, "Introducing EDEN ISS - A European project on advancing plant cultivation technologies and operations," *45th International Conference on Environmental Systems, 12-16 July 2015, Washington, USA*, 2015.

[58] W. Broll, "Augmentierte Realität," in *EXamen.press, Virtual und augmented reality (VR / AR)*, R. Dörner, W. Broll, P. Grimm, and B. Jung, Eds., Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 241–294.

[59] T. Suthau, "Augmented Reality: Positionsgenaue Einblendung räumlicher Informationen in einem See Through Head Mounted Display für die Medizin am Beispiel der Leberchirurgie," Dissertation, Fakultät VI, Technischen Universität Berlin, Berlin, 2006.

[60] M. von Atzigen, F. Liebmann, A. Hoch, D. E. Bauer, J. G. Snedeker, M. Farshad, and P. Fürnstahl, "HoloYolo: A proof-of-concept study for marker-less surgical navigation of spinal rod implants with augmented reality and on-device machine learning," *The international journal of medical robotics + computer assisted surgery : MRCAS*, vol. 17, no. 1, pp. 1–10, 2021, doi: 10.1002/rcs.2184.

[61] D. van Krevelen and R. Poelman, "A survey of augmented reality technologies, applications and limitations," *IJVR*, vol. 9, no. 2, pp. 1–20, 2010, doi: 10.20870/IJVR.2010.9.2.2767.

[62] M. Safi, J. Chung, and P. Pradhan, "Review of augmented reality in aerospace industry," *AEAT*, vol. 91, no. 9, pp. 1187–1194, 2019, doi: 10.1108/AEAT-09-2018-0241.

[63] R. Palmarini, J. A. Erkoyuncu, R. Roy, and H. Torabmostaedi, "A systematic review of augmented reality applications in maintenance," *Robotics and Computer-Integrated Manufacturing*, vol. 49, pp. 215–228, 2018, doi: 10.1016/j.rcim.2017.06.002.

[64] B. H. Limbu, H. Jarodzka, R. Klemke, and M. Specht, "Using sensors and augmented reality to train apprentices using recorded expert performance: A systematic literature review," *Educational Research Review*, vol. 25, pp. 1–22, 2018, doi: 10.1016/j.edurev.2018.07.001.

[65] M. Caria, G. Sara, G. Todde, M. Polese, and A. Pazzona, "Exploring smart glasses for augmented reality: A valuable and integrative tool in precision livestock farming," *Animals*, vol. 9, no. 11, 2019, doi: 10.3390/ani9110903.

[66] Z. Zhao, W. Yang, W. Chinthammit, R. Rawnsley, P. Neumeyer, and S. Cahoon, "A New Approach to Utilize Augmented Reality on Precision Livestock Farming," in *Proceedings of the International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments*, 2017, pp. 185–188.

[67] H. Bernhardt, "Technik in der Rinderhaltung," in vol. 30, *Jahrbuch Agrartechnik 2018*, L. Frerichs, Ed., Braunschweig, 2019, pp. 1–13.

[68] M. Agan, L. Voisinet, and A. Devereaux, "NASA's Wireless Augmented Reality Prototype (WARP)," in *AIP Conference Proceedings 420*, Albuquerque,New Mexico (USA), 1998, pp. 236–242.

[69] NASA JPL, *Wiring the fashion trend of the future.* [Online]. Available: https://www.jpl.nasa.gov/news/wiring-the-fashion-trend-of-the-future (accessed: Feb. 4 2022).

[70] D. Tingdahl, D. de Weerdt, M. Vergauwen, and L. van Gool, "WEAR++: 3D model driven camera tracking on board the International Space Station," in *2011 International Conference on 3D Imaging (IC3D)*, Liege, Belgium, 2011, pp. 1–8.

[71] F. Scheid, A. Nitsch, H. König, L. Arguello, D. de Weerdt, D. Arndt, and S. Rakers, "Operation of European SDTO at Col-CC," in *SpaceOps 2010 Conference*, Huntsville, Alabama, 2010.

[72] A. Boyd, A. Fortunato, M. Wolff, and D. M. Oliveira, "mobiPV: A new, wearable real-time collaboration software for astronauts using mobile computing solutions," in *SpaceOps 2016 Conference*, Daejeon, Korea, 2016.

[73] M. Wolff, D. M. Oliveira, A. Fortunato, A. Boyd, and A. Cowley, "Enhancement of the ESA mobile Procedure Viewer (mobiPV) beyond Low Earth Orbit," *68th International Astronautical Congress 2017, Sep 2017, Adelaide, Australia*, 2017.

[74] K. Chintamani, B. van Lierde, S. Maloney, P. Kiernan, and Oliveira, David M. and Wolff, Mikael, "Wearable crew support technology on the International Space Station: the mobile Procedure Viewer (mobiPV)," in *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2013 Annual Conference*, D. de Waard, K. Brookhuis, R. Wiczorek, F. Di Nocera, P. Barham, C. Weikert, A. Kluge, and Gerbino, W. and Toffetti, A. (Eds.), Eds., 2014.

[75] VTT, Thales Alenia Space, ICCS, and ESA, "EdcAR: Executive summary report (AO/1-8100/14/NL/MH)," Augmented Reality for AIT, AIV and Operations, Dec. 2016.

[76] NASA, *NASA, Microsoft collaborate to bring science fiction to science fact.* [Online]. Available: https://www.nasa.gov/press-release/nasa-microsoft-collaborate-to-bring-science-fiction-to-science-fact (accessed: Jun. 10 2022).

[77] NASA, *Sidekick.* [Online]. Available: https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Investigation.html?#id=2018 (accessed: Jun. 10 2022).

[78] NASA, *T2 Treadmill augmented reality procedures.* [Online]. Available: https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Investigation.html?#id=7587 (accessed: Jun. 11 2022).

[79] NASA, *New augmented reality applications assist astronaut repairs to Space Station.* [Online]. Available: https://www.nasa.gov/mission_pages/station/research/news/augmented-reality-applications-assist-astronauts (accessed: Jun. 11 2022).

[80] N. Ahsan, M. Andersen, P. Baldwin, J. Brown, N. Chapman-Weems, and C. H. Estevez, "An augmented reality guidance and operations system to support the Artemis program and future EVAs," *50th International Conference on Environmental Systems, 12-15 July 2021, Virtual Event*, 2021.

[81] P. Mitra, B. Krygier, S. Nandwani, M. Noyes, T. Garrett, A. Smith, V. Selvakumar, and M. J. Miller, "Trades, architecture, and design of the Joint Augmented Reality Visual Informatics System (Joint AR) product," *52nd International Conference on Environmental Systems, 16-20 July 2023, Calgary, Alberta, Canada*, 2023.

[82] M. J. Fornito II, N. Lopac, G. Russell, J. G. Demartini, R. Flanagan, L. Miller, and M. Young, "Design of an augmented reality user interface for lunar extravehicular activity operations," *52nd International Conference on Environmental Systems, 16-20 July 2023, Calgary, Alberta, Canada*, 2023.

[83] M. Xi, M. Adcock, and J. McCulloch, "Future agriculture farm management using augmented reality," in *2018 IEEE Workshop on Augmented and Virtual Realities for Good (VAR4Good)*, Reutlingen, 2018, pp. 1–3.

[84] W. Hurst, F. R. Mendoza, and B. Tekinerdogan, "Augmented reality in precision farming: Concepts and applications," *Smart Cities*, vol. 4, no. 4, pp. 1454–1468, 2021, doi: 10.3390/smartcities4040077.

[85] A. M. Braly, B. Nuernberger, and S. Y. Kim, "Augmented reality improves procedural work on an International Space Station science instrument," *Human factors*, vol. 61, no. 6, pp. 866–878, 2019, doi: 10.1177/0018720818824464.

[86] R. Alarcon, F. Wild, C. Perey, M. M. Genescà, J. G. Martínez, J. X. Ruiz Martí, M. J. Simon Olmos, and D. Dubert, "Augmented reality for the enhancement of space product assurance and safety," *Acta Astronautica*, vol. 168, pp. 191–199, 2020, doi: 10.1016/j.actaastro.2019.10.020.

[87] D. M. Lengyel and J. S. Newman, "International Space Station lessons learned for space exploration," 2014. Accessed: Jul. 13 2022. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/iss_lessons_learned.pdf

[88] D. Brinkmeyer and R. Müller, "Entscheidungsunterstützung mit dem AHP," *Zeitschrift für Agrarinformatik*, vol. 2, no. 5, pp. 82–92, 1994.

[89] O. Meixner and R. Haas, *Computergestützte Entscheidungsfindung: Expert choice und AHP - innovative Werkzeuge zur Lösung komplexer Probleme*. Frankfurt [Main]: Redline Wirtschaft bei Ueberreuter, 2003.

[90] T. L. Saaty, "Decision making with the analytic hierarchy process," *International Journal of Services Sciences*, vol. 1, no. 1, pp. 83–98, 2008, doi: 10.1504/IJSSCI.2008.017590.

[91] G. Woeckner, "System analysis of integration paths for augmented reality technology in greenhouses as part of future extraterrestrial habitats," Master thesis, Institute of Space Systems, Technical University of Braunschweig, 2020.

[92] L. Poulet, K. Engeling, T. Hatch, S. Stahl-Rommel, Y.-A. Velez Justiniano, S. Castro-Wallace, J. Bunchek, O. Monje, M. Hummerick, C. L. M. Khodadad, L. E. Spencer, J. Pechous, C. M. Johnson, R. Fritsche, G. D. Massa, M. W. Romeyn, A. E. O'Rourke, and R. M. Wheeler, "Large-scale crop production for the Moon and Mars: Current gaps and future perspectives," *Front. Astron. Space Sci.*, vol. 8, 2022, doi: 10.3389/fspas.2021.733944.

[93] N. S. Beisel, J. B. Callaham, N. J. Sng, D. J. Taylor, A.-L. Paul, and R. J. Ferl, "Utilization of single-image normalized difference vegetation index (SI-NDVI) for early plant stress detection," *Applications in plant sciences*, vol. 6, no. 10, e01186, 2018, doi: 10.1002/aps3.1186.

[94] C. Zeidler, P. Zabel, V. Vrakking, M. Dorn, M. Bamsey, D. Schubert, A. Ceriello, R. Fortezza, D. de Simone, C. Stanghellini, F. Kempkes, E. Meinen, A. Mencarelli, G.-J. Swinkels, A.-L. Paul, and R. J. Ferl, "The plant health monitoring system of the EDEN ISS space greenhouse in Antarctica during the 2018 experiment phase," *Frontiers in Plant Science*, 10:1457, 2019, doi: 10.3389/fpls.2019.01457.

[95] R. Tucker, J. A. Callaham, C. Zeidler, A.-L. Paul, and R. J. Ferl, "NDVI imaging within space exploration plant growth modules – A case study from EDEN ISS Antarctica," *Life Sciences in Space Research*, vol. 26, pp. 1–9, 2020, doi: 10.1016/j.lssr.2020.03.006.

[96] J. Brunet, O. Gerbi, P. Andre, E. Davin, R. A. Rodriguez, F. Carbonero, E. Soumalainen, and C. Lasseur, "Alisse : Advanced life support system evaluator," *38th COSPAR Scientific Assembly*, 2010.

[97] M. Cooper, M. Perchonok, and G. L. Douglas, "Initial assessment of the nutritional quality of the space food system over three years of ambient storage," *NPJ microgravity*, vol. 3, p. 17, 2017, doi: 10.1038/s41526-017-0022-z.

[98] R. M. Wheeler, "Carbon balance in bioregenerative life support systems: some effects of system closure, waste management, and crop harvest index," *Advances in Space Research*, vol. 31, no. 1, pp. 169–175, 2003, doi: 10.1016/S0273-1177(02)00742-1.

[99] G. D. Massa, R. M. Wheeler, R. C. Morrow, and H. G. Levine, "Growth chambers on the International Space Station for large plants," *Acta Hortic.*, no. 1134, pp. 215–222, 2016, doi: 10.17660/ActaHortic.2016.1134.29.

[100] G. D. Massa, N. F. Dufour, J. A. Carver, M. E. Hummerick, R. M. Wheeler, R. C. Morrow, and T. M. Smith, "VEG-01: Veggie hardware validation testing on the International Space Station," *Open Agriculture*, vol. 2, no. 1, pp. 33–41, 2017, doi: 10.1515/opag-2017-0003.

[101] NASA, *Ph-01: An integrated omics guided approach to lignification and gravitational responses: The final frontier.* [Online]. Available: https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Investigation.html?#id=2032 (accessed: Jun. 25 2023).

[102] S. H. Schwartzkopf, "Lunar base controlled ecological life support system (LCELSS): Preliminary conceptual design study," Tech. Rep. NASA-CR-188479, Apr. 1991.

[103] S. Campana and D. Melendez, "Cold stowage flight systems," *41st International Conference on Environmental Systems; 17-21 July 2011, Portland, Oregon, USA*, 2011, doi: 10.2514/6.2011-5261.

[104] V. Vrakking, M. Bamsey, C. Zeidler, P. Zabel, D. Schubert, and O. Romberg, "Service Section design of the EDEN ISS project," *47th International Conference on Environmental Systems, 16-20 July 2017, Charleston, South Carolina, USA*, 2017.

[105] P. Zabel, M. Bamsey, C. Zeidler, V. Vrakking, D. Schubert, and O. Romberg, "Future Exploration Greenhouse design of the EDEN ISS project," *47th International Conference on Environmental Systems, 16-20 July 2017, Charleston, South Carolina, USA*, 2017.

[106] J. Fahrion, C. Fink, P. Zabel, D. Schubert, M. Mysara, R. van Houdt, B. Eikmanns, K. Beblo-Vranesevic, and P. Rettberg, "Microbial monitoring in the EDEN ISS greenhouse, a Mobile Test Facility in Antarctica," *Frontiers in microbiology*, vol. 11, p. 525, 2020, doi: 10.3389/fmicb.2020.00525.

[107] P. Zabel, C. Zeidler, V. Vrakking, and D. Schubert, "Implications of different plant cultivation techniques for food production in space based on experiments in EDEN ISS," *International Conference on Environmental Systems*, 2020.

[108] C. Zeidler, V. Vrakking, P. Zabel, M. Bamsey, and D. Schubert, "Resource consumption and waste production of the EDEN ISS space greenhouse analogue during the 2018 experiment phase in Antarctica," *International Conference on Environmental Systems*, 2020.

[109] G. Boscheri, G. Marchitelli, C. Lobascio, A. Saverino, and P. Zabel, "EDEN ISS Rack-like food production unit: results after mission in Antarctica," *49th International Conference on Environmental Systems, 7-11 July 2019, Boston, Massachusetts, USA*, 2019.

[110] I. L. Schlacht, H. Kolrep, S. Daniel, and G. Musso, "Impact of plants in ssolation: The EDEN-ISS human factors investigation in Antarctica," in *Advances in Intelligent Systems and Computing, Advances in Human Factors of Transportation*, N. Stanton, Ed., Cham: Springer International Publishing, 2020, pp. 794–806.

[111] R. Odeh and C. L. Guy, "Gardening for therapeutic people-plant interactions during long-duration space missions," *Open Agriculture*, vol. 2, no. 1, pp. 1–13, 2017, doi: 10.1515/opag-2017-0001.

[112] S. C. Bates and J. Marquit, "Space psychology: natural elements in habitation design," *Pers Ubiquit Comput*, vol. 15, no. 5, pp. 519–523, 2011, doi: 10.1007/s00779-010-0316-6.

[113] C. Zeidler, V. Vrakking, M. Bamsey, L. Poulet, P. Zabel, D. Schubert, C. Paille, E. Mazzoleni, and N. Domurath, "Greenhouse module for space system: A lunar greenhouse design," *Open Agriculture*, vol. 2, no. 1, pp. 116–132, 2017, doi: 10.1515/opag-2017-0011.

[114] G. D. Massa, R. M. Wheeler, G. W. Stutte, J. T. Richards, L. E. Spencer, M. E. Hummerick, G. L. Douglas, and T. Sirmons, "Selection of leafy green vegetable varieties for a pick-and-eat diet supplement on ISS," *45th International Conference on Environmental Systems, 12-16 July 2015, Bellevue, Washington, USA*, 2015.

[115] V. M. Paradiso, M. Castellino, M. Renna, C. E. Gattullo, M. Calasso, R. Terzano, I. Allegretta, B. Leoni, F. Caponio, and P. Santamaria, "Nutritional characterization and shelf-life of packaged microgreens," *Food & function*, vol. 9, no. 11, pp. 5629–5640, 2018, doi: 10.1039/C8FO01182F.

[116] T. W. Tibbits and D. Alford, "Controlled ecological life support system: Use of higher plants," NASA-CP-2231, 1982.

[117] J. E. Hoff, J. M. Howe, and C. A. Mitchell, "Nutritional and cultural aspects of plant species selection for a controlled ecological life support system," NASA Ames Research Center Technical Report NSG 2401 and NSG 2404, 1982.

[118] R. M. Wheeler, "Agriculture for space: People and places paving the way," *Open Agriculture*, vol. 2, no. 1, 2017, doi: 10.1515/opag-2017-0002.

[119] R. M. Wheeler, J. C. Sager, W. L. Berry, C. L. Mackowiak, G. W. Stutte, N. C. Yorio, and L. M. Ruffe, "Nutrient, acid, and water budgets of hydroponically grown crops," *Acta Hortic.*, no. 481, pp. 655–662, 1999, doi: 10.17660/ActaHortic.1999.481.78.

[120] K. A. Corey and R. M. Wheeler, "Gas exchange in NASA's Biomass Production Chamber," *BioScience*, vol. 42, no. 7, pp. 503–509, 1992, doi: 10.2307/1311880.

[121] B. Bugbee and O. Monje, "The limits of crop productivity: validating theoretical estimates and determining the factors that limit crop yields in optimal environments," *BioScience*, vol. 42, no. 7, pp. 494–502, 1992.

[122] S. M. Smith, S. R. Zwart, G. Block, B. L. Rice, and J. E. Davis-Street, "The nutritional status of astronauts is altered after long-term space flight aboard the International Space Station," *The Journal of nutrition*, vol. 135, no. 3, pp. 437–443, 2005, doi: 10.1093/jn/135.3.437.

[123] G. Douglas, M. R. Cooper, D. Bermúdez-Aguirre, and T. Sirmons, "Evidence report - Risk of performance decrement and crew illness due to an inadequate food system," Human Research Program Space. Human Factors and Habitability Element, Houston, Texas JSC-CN-37577, 2016.

[124] T. Bringslimark, T. Hartig, and G. G. Patil, "The psychological benefits of indoor plants: A critical review of the experimental literature," *Journal of Environmental Psychology*, vol. 29, no. 4, pp. 422–433, 2009, doi: 10.1016/j.jenvp.2009.05.001.

[125] Australian Antarctic Division, "Initial environmental evaluation of the proposal to introduce hydroponic operations at Australian Antarctic stations," Australian Antarctic Division, 1994.

[126] Y. Berkovich, S. O. Smolyanina, N. M. Krivobok, A. N. Erokhin, A. N. Agureev, and N. A. Shanturin, "Vegetable production facility as a part of a closed life support system in a Russian Martian space flight scenario," *Advances in Space Research*, vol. 44, no. 2, pp. 170–176, 2009, doi: 10.1016/j.asr.2009.03.002.

[127] D. Głąbska, D. Guzek, B. Groele, and K. Gutkowska, "Fruit and vegetable intake and mental health in adults: A systematic review," *Nutrients*, vol. 12, no. 1, 2020, doi: 10.3390/nu12010115.

[128] R. M. Wheeler, J. C. Sager, R. P. Prince, W. M. Knott, C. L. Mackowiak, G. W. Stutte, N. C. Yorio, L. M. Ruffe, B. V. Peterson, G. D. Goins, C. R. Hinkle, and W. L. Berry, "Crop production for advanced life support systems - Observations from the Kennedy Space Center breadboard project," Florida NASA/TM-2003-211184, 2003.

[129] P. Sadler, G. Giacomelli, R. Patterson, M. Kacira, R. Furfaro, C. Lobascio, G. Boscheri, M. Lamantea, L. Grizzaffi, S. Rossignoli, M. Pirolli, and S. DePascale, "Bio-regenerative life support systems for space surface applications," *41st International Conference on Environmental Systems; 17-21 July 2011, Portland, Oregon, USA*, 2011, doi: 10.2514/6.2011-5133.

[130] P. Zabel, M. Bamsey, C. Zeidler, V. Vrakking, D. Schubert, O. Romberg, G. Boscheri, and T. Dueck, "The preliminary design of the EDEN ISS Mobile Test Facility - An Antarctic greenhouse," *46th International Conference on Environmental Systems, 10-14 July 2016, Vienna, Austria*, 2016c.

[131] P. Zabel and C. Zeidler, "EDEN ISS: A plant cultivation technology for spaceflight," in *Handbook of life support systems for spacecraft and extraterrestrial habitats*, E. Seedhouse and D. J. Shayler, Eds.: Springer, Cham, 2019, pp. 1–15.

[132] E. Kohlberg, C. Wesche, U. Nixdorf, and D. Mengedoht, "Development of telemedicine: A substantial contribution to medical safety during winter-over," in *Proceedings of the COMNAP Symposium 2016: Winter-Over Challenges, Goa, India, 19 & 20 August, 2016*, Christchurch, New Zealand: Council of Managers of National Antarctic Programs, 2017, pp. 109–113.

[133] M. S. Anderson, M. K. Ewert, J. F. Keener, and S. A. Wagner, "Life support baseline values and assumptions document," Houston, Texas NASA/TP-2015–218570, 2015.

[134] R. L. Patterson, "Description, operation and production of the South Pole Food Growth Chamber (SPFGC)," Master thesis, Faculty of the Department of Agricultural and Biosystems Engineering, University of Arizona, Tucson, 2011.

[135] V. Vrakking, D. Schubert, P. Zabel, C. Zeidler, M. Dorn, R. Ferl, and A.-L. Paul, "EDEN ISS – greenhouse in Antarctica," in vol. 745, *Expeditions to Antarctica: ANT-Land 2019/20 Neumayer Station III, Kohnen Station, flight operations and field campaigns*, T. Fromm, C. Oberdieck, T. Matz, and C. Wesche, Eds., 2020, pp. 54–61.

[136] S. Rubio, E. Diaz, J. Martin, and J. M. Puente, "Evaluation of subjective mental workload: A comparison of SWAT, NASA-TLX, and workload profile methods," *Applied Psychology*, vol. 53, no. 1, pp. 61–86, 2004, doi: 10.1111/j.1464-0597.2004.00161.x.

[137] S. Kang, Y. Ozaki, K.-C. Ting, and A.-J. Both, "Automation for biomass production within advanced life support systems," *IFAC Proceedings Volumes*, vol. 33, no. 29, pp. 275–280, 2000, doi: 10.1016/S1474-6670(17)36790-3.

[138] T. Dueck, F. Kempkes, E. Meinen, and C. Stanghellini, "Choosing crops for cultivation in space," *46th International Conference on Environmental Systems, 10-14 July 2016, Vienna, Austria*, 2016.

[139] D. Schubert, "Greenhouse production analysis of early mission scenarios for Moon and Mars habitats," *Open Agriculture*, vol. 2, no. 1, 2017, doi: 10.1515/opag-2017-0010.

[140] R. A. Grier, "How high is high? A meta-analysis of NASA-TLX global workload scores," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 59, no. 1, pp. 1727–1731, 2015, doi: 10.1177/1541931215591373.

[141] P. Ø. Braarud, "An efficient screening technique for acceptable mental workload based on the NASA Task Load Index—development and application to control room validation," *International Journal of Industrial Ergonomics*, vol. 76, p. 102904, 2020, doi: 10.1016/j.ergon.2019.102904.

[142] G. D. Massa, J. M. Bunchek, G. L. Douglas, M. E. Hummerick, C. A. Mitchell, R. C. Morrow, A. H. Morsi, P. G. Roma, M. W. Romeyn, L. E. Spencer, and R. M. Wheeler, *VEG-04: The effects of light quality on Mizuna Mustard growth, nutritional composition, and organoleptic acceptability for a space diet.* [Online]. Available: https://ntrs.nasa.gov/citations/20200000639 (accessed: Jan. 5 2024).

[143] J. V. Pauly, J. M. Bunchek, D. F. Dinges, M. Basner, S. Park-Chavar, M. Kaizi-Lutu, P. G. Roma, R. M. Wheeler, G. D. Massa, R. F. Fritsche, and A. C. Stahn, "Veggie on ICE: The effects of plant production on human behavioral health in long-duration Antarctic overwintering missions," *NASA Human Research Program Investigators' Workshop*, 2023.

[144] P. Zabel, D. Schubert, M. Dorn, J. Bunchek, and V. Vrakking, "Summary of research and outreach activities during the 2021 season of the EDEN ISS Antarctic greenhouse," *51st International Conference on Environmental Systems, 10-14 July 2022, St. Paul, Minnesota, USA*, 2022.

[145] ISECG, "Global Exploration Roadmap - Supplement August 2020: Lunar surface exploration scenario update," NP-2020-07-2888-HQ, Aug. 2020.

[146] C. Zeidler and G. Woeckner, "Using augmented reality in a planetary surface greenhouse for crew time optimization," *ACM CHI 2021, SpaceCHI: Workshop on Human-Computer Interaction for Space Exploration, Virtual Conference, 14.05.2021*, 2021.

[147] T. Gries, F. Schreiber, and M. Kemper, "Textil 4.0," in *Handbuch Industrie 4.0: Recht, Technik, Gesellschaft*, W. Frenz, Ed., Berlin, Heidelberg: Springer Berlin Heidelberg, 2020, pp. 603–617.

[148] M. Wingen and H. Schüttrumpf, "Wasserwirtschaft 4.0," in *Handbuch Industrie 4.0: Recht, Technik, Gesellschaft*, W. Frenz, Ed., Berlin, Heidelberg: Springer Berlin Heidelberg, 2020, pp. 799–820.

[149] A. Katsaros and E. Keramopoulos, "FarmAR, a farmer's augmented reality application based on semantic web," in *2017 South Eastern European Design Automation, Computer Engineering, Computer Networks and Social Media Conference (SEEDA-CECNSM)*, Kastoria, 2017, pp. 1–6.

[150] A. Katsaros, E. Keramopoulos, and M. Salampasis, "A prototype application for cultivation optimization using augmented reality," *8th International Conference on Information and Communication Technologies in Agriculture, Food & Environment*, pp. 805–811, 2017.

[151] M. C. Neto and P. Cardoso, "Augmented reality greenhouse," *EFITA-WCCA-CIGR Conference "Sustainable Agriculture through ICT Innovation", Turin, Italy, 24-27 June 2013.*, 2013.

[152] A. Nigam, P. Kabra, and P. Doke, "Augmented reality in agriculture," in *2011 IEEE 7th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, Shanghai, China, 2011, pp. 445–448.

[153] T. Shaleendra, B. T. Wishvamali, N. Gunarathne, S. Hareendran, and P. Abeygunawardhana, "Simulation of the influence of environmental factors related to greenhouses using augmented reality," in *2019 International Seminar on Research of Information Technology and Intelligent Systems (ISRITI)*, Yogyakarta, Indonesia, 2019, pp. 462–467.

[154] I. Bekiaris, A. Leonidis, M. Korozi, C. Stratakis, E. Zidianakis, M. Doxastaki, and C. Stephanidis, "GRETA: Pervasive and AR interfaces for controlling intelligent greenhouses," in *2021 17th International Conference on Intelligent Environments (IE)*, Dubai, United Arab Emirates, 2021, pp. 1–8.

[155] T. Balint and P. Pangaro, "The emerging roles of the observer on human space missions: Curated autonomy through boundary objects," *68th International Astronautical Congress 2017, Sep 2017, Adelaide, Australia*, 2017.

[156] S. Abood, "Martian environmental psychology: The choice architecture of a Mars mission and colony," in *Space and Society, The human factor in a mission to Mars: An Interdisciplinary Approach*, K. Szocik, Ed., Cham: Springer International Publishing, 2019, pp. 3–34.

[157] A. Bahnmüller, "Evaluation of interaction techniques for early phase satellite design in immersive augmented reality," Master thesis, Chemnitz University of Technology, 2019.

[158] A. Bahnmüller, A. S. Muhammad, G. Albuquerque, and A. Gerndt, "Evaluation of interaction techniques for early phase satellite design in immersive AR," in *2020 IEEE Aerospace Conference*, Big Sky, MT, USA, 2020, pp. 1–8.

[159] B. Nuernberger, R. Tapella, S.-H. Berndt, S. Y. Kim, S. Samochina, M. Tory, and D. F. Keefe, "Under water to outer space: Augmented reality for astronauts and beyond," *IEEE*

computer graphics and applications, vol. 40, no. 1, pp. 82–89, 2020, doi: 10.1109/MCG.2019.2957631.

[160] B. Nuernberger, "XR in the NASA mission lifecycle with ProtoSpace: Case Study," Online, Oct. 6 2021. Accessed: Jul. 18 2022. [Online]. Available: https://www.youtube.com/watch?v=yF_JE6IsvTI

[161] OpsLab JPL, *ProtoSpace: Building spacecraft in augmented reality.* [Online]. Available: https://www.youtube.com/watch?v=dD0FoH8M1EM (accessed: Jul. 28 2022).

[162] S. P. Abercrombie, A. Menzies, V. Luo, A. Winter, M. Clausen, B. Duran, M. Jorritsma, C. Goddard, Lidawer, and Alana, "OnSight: Multi-platform visualization of the surface of Mars," *American Geophysical Union, Fall Meeting 2017*, 2017.

[163] S. P. Abercrombie, A. Menzies, H. E. Abarca, V. X. Luo, S. Samochina, M. T. Trautman, L. A. Klyne, S. A. Fernadez, A. H. Lidawer, J. R. Pamer, A. B. Winter, R. Crocco, M. A. Vona, and A. J. Byon, "Multi-platform immersive visualization of planetary, asteroid, and terrestrial analog terrain," *50th Lunar and Planetary Science Conference 2019*, 2019.

[164] K. Montgomery, G. Thonier, M. Stephanides, and S. Schendel, "Virtual reality based surgical assistance and training system for long duration space missions," *Studies in health technology and informatics*, vol. 81, pp. 315–321, 2001.

[165] VTT, Skytek, and ESA, "AROGAN - Augmented reality based orbit and ground applications: Executive summary report (4000127710/19/NL/GLC)," Procedure viewer and authoring tool for ground AIV/AIT applications, Dec. 2021.

[166] L. Ravagnolo, K. Helin, I. Musso, R. Sapone, C. Vizzi, F. Wild, A. Vovk, B. Limbu, M. Ransley, C. Smith, and J. Rasool, "Enhancing crew training for exploration missions: The Wekit experience," *70th International Astronautical Congress 2019, Oct 2019, Washington, USA*, 2019.

[167] D. Datcu, M. Cidota, S. Lukosch, D. M. Oliveira, S. Agostinho, and M. Wolff, *Augmented reality enabled collaboration.* [Online]. Available: https://indico.esa.int/event/71/contributions/3153/attachments/2505/2883/1100_-_M._Wolff.pdf (accessed: Feb. 13 2022).

[168] D. Datcu, M. Cidota, S. Lukosch, D. M. Oliveira, and M. Wolff, "Virtual co-location to support remote assistance for inflight maintenance in ground training for space missions," in *Proceedings of the 15th International Conference on Computer Systems and Technologies - CompSysTech '14*, Ruse, Bulgaria, 2014, pp. 134–141.

[169] D. Markov-Vetter, "Human factors in instructional augmented reality for intravehicular spaceflight activities and How gravity influences the setup of interfaces operated by direct object selection," Dissertation, Faculty of Computer Science and Electrical Engineering, University Rostock, Rostock, 2016.

[170] Y. Nevatia, K. Chintamani, T. Meyer, T. Blum, A. Runge, and N. Fritz, "Computer aided medical diagnosis and surgery system: towards automated medical diagnosis for long term space missions," 2011.

[171] L. Arguello, D. de Weerdt, M. Ilzkovitz, T. Meyer, and R. Ambrus, *WEAR WEarable Augmented Reality.* [Online]. Available: https://www.esa.int/gsp/ACT/doc/EVENTS/bmiworkshop/ACT-PRE-BNG-WEAR(BMI_Workshop).pdf (accessed: Feb. 13 2022).

[172] S. Bhardwaj, A. Suresh, R. Arora, S. Vasishth, D. Laha, D. Gaba, and S. Bhambri, "Isolated bio-regenerative system for vertical farming through robots in space explorations," in *Advances in Intelligent Systems and Computing, Robot intelligence technology and applications 5: Results from the 5th International Conference on Robot Intelligence Technology and Applications*, J.-H. Kim, H. Myung, J. Kim, W. Xu, E. T. Matson, J.-W. Jung, and H.-L. Choi, Eds., Cham: Springer International Publishing, 2019, pp. 251–262.

[173] J. Redmon, S. Divvala, R. Girshick, and A. Farhadi, "You Only Look Once: Unified, real-time object detection," 2015.

[174] Y.-Y. Zheng, J.-L. Kong, X.-B. Jin, X.-Y. Wang, T.-L. Su, and M. Zuo, "CropDeep: The crop vision dataset for deep-learning-based classification and detection in precision agriculture," *Sensors (Basel, Switzerland)*, vol. 19, no. 5, 2019, doi: 10.3390/s19051058.

[175] Y. Yu, K. Zhang, H. Liu, L. Yang, and D. Zhang, "Real-time visual localization of the picking points for a ridge-planting strawberry harvesting robot," *IEEE Access*, vol. 8, pp. 116556–116568, 2020, doi: 10.1109/ACCESS.2020.3003034.

[176] G. Zhaoxin, L. Han, Z. Zhijiang, and P. Libo, "Design a robot system for tomato picking based on YOLO v5," *IFAC-PapersOnLine*, vol. 55, no. 3, pp. 166–171, 2022, doi: 10.1016/j.ifacol.2022.05.029.

[177] M. Klug, "Nutzung der HoloLens 2 für die Pflanzenerkennung und Augmentierung im Kontext des EDEN ISS Weltraumgewächshauses," Master thesis, Fachbereich 03 – Mathematik/Informatik, Universität Bremen, 2022.

[178] G. Jocher, A. Stoken, A. Chaurasia, J. Borovec, NanoCode012, TaoXie, Y. Kwon, K. Michael, L. Changyu, J. Fang, Abhiram V, Laughing, tkianai, yxNONG, P. Skalski, A. Hogan, J. Nadar, imyhxy, L. Mammana, A. Wang, C. Fati, D. Montes, J. Hajek, L. Diaconu, M. T. Minh, Marc, albinxavi, fatih, oleg, and wanghaoyang, *ultralytics/yolov5: v6.0 - YOLOv5n 'Nano' models, roboflow integration, TensorFlow export, OpenCV DNN support*: Zenodo, 2021.

[179] G. Liu, J. C. Nouaze, P. L. Touko Mbouembe, and J. H. Kim, "YOLO-Tomato: A robust algorithm for tomato detection based on YOLOv3," *Sensors (Basel, Switzerland)*, vol. 20, no. 7, 2020, doi: 10.3390/s20072145.

[180] T.-Y. Lin, M. Maire, S. Belongie, J. Hays, P. Perona, D. Ramanan, P. Dollár, and C. L. Zitnick, "Microsoft COCO: Common objects in context," in *Lecture Notes in Computer Science, Computer vision – ECCV 2014*, D. Fleet, T. Pajdla, B. Schiele, and T. Tuytelaars, Eds., Cham: Springer International Publishing, 2014, pp. 740–755.

[181] G. Jocher, *Tips for best training results.* [Online]. Available: https://github.com/ultralytics/yolov5/wiki/Tips-for-Best-Training-Results (accessed: 02.03.24).

[182] K. T. Claypool and M. Claypool, "On frame rate and player performance in first person shooter games," *Multimedia Systems*, vol. 13, no. 1, pp. 3–17, 2007, doi: 10.1007/s00530-007-0081-1.

[183] A. Bochkovskiy, C.-Y. Wang, and H.-Y. M. Liao, "YOLOv4: Optimal speed and accuracy of object detection," 2020. [Online]. Available: http://arxiv.org/pdf/2004.10934v1

[184] M. Mekni and A. Lemieux, "Augmented reality: Applications, challenges and future trends," *Applied computational science*, vol. 20, pp. 205–214, 2014.

[185] C. Cram, K. Doty, M. Frances, M. Laing, and A. Tullis, "Augmented reality navigation and information display systems for astronauts on the lunar surface, ARSIS 5.0," *ACM CHI 2022, SpaceCHI: Workshop on Human-Computer Interaction for Space Exploration, Hybrid Conference, 01.05.2022, New Orleans, Louisiana, USA*, 2022.

[186] C. Paige, F. Ward, T. Piercy, and D. Newman, "A virtual reality mission simulation system for lunar rover missions," *ACM CHI 2021, SpaceCHI: Workshop on Human-Computer Interaction for Space Exploration, Virtual Conference, 14.05.2021*, 2021.

[187] S. P. Mohanty, D. P. Hughes, and M. Salathé, "Using deep learning for image-based plant disease detection," *Frontiers in Plant Science*, vol. 7, p. 1419, 2016, doi: 10.3389/fpls.2016.01419.

[188] M. P. Mathew and T. Y. Mahesh, "Leaf-based disease detection in bell pepper plant using YOLO v5," *SIViP*, vol. 16, no. 3, pp. 841–847, 2022, doi: 10.1007/s11760-021-02024-y.

[189] A. Ahmad, D. Saraswat, and A. El Gamal, "A survey on using deep learning techniques for plant disease diagnosis and recommendations for development of appropriate tools," *Smart Agricultural Technology*, vol. 3, p. 100083, 2023, doi: 10.1016/j.atech.2022.100083.

[190] A. Anyamba and C. J. Tucker, "Historical perspectives on AVHRR NDVI and vegetation drought monitoring," in *Remote sensing of drought*, B. D. Wardlow, M. C. Anderson, and J. P. Verdin, Eds.: CRC Press, 2012, pp. 23–52.

[191] G. T. Yengoh, D. Dent, L. Olsson, A. E. Tengberg, and C. J. Tucker III, *Use of the normalized difference vegetation index (NDVI) to assess land degradation at multiple scales: Current status, future trends, and practical considerations*. Cham: Springer International Publishing, 2016.

[192] P. Mishra, M. S. M. Asaari, A. Herrero-Langreo, S. Lohumi, B. Diezma, and P. Scheunders, "Close range hyperspectral imaging of plants: A review," *Biosystems Engineering*, vol. 164, pp. 49–67, 2017, doi: 10.1016/j.biosystemseng.2017.09.009.

[193] L. Kuhr, "Implementation of in-situ plant health visualization for controlled environment agriculture using Microsoft HoloLens 2," Master thesis, Institut für Werkzeugmaschinen und Fertigungstechnik, Technische Universität Braunschweig, 2022.

[194] T. Hayashi, *HoloLens2 camera mount.* [Online]. Available: https://www.thingiverse.com/thing:4139589 (accessed: Dec. 17 2022).

[195] J. Brooke, "SUS: A retrospective," *Journal of Usability Studies*, vol. 8, no. 2, pp. 29–40, 2013.

[196] J. Brooke, "SUS - A quick and dirty usability scale," in *Usability evaluation in industry*, P. W. Jordan, B. Thomas, B. A. Weerdmeester, and I. L. McClelland, Eds.: Taylor and Francis, 1996, pp. 189–194.

[197] F. Wild, R. Klemke, P. Lefrere, M. Fominykh, and T. Kuula, "Technology acceptance of augmented reality and wearable technologies," in *Communications in Computer and Information Science, Immersive learning research network*, D. Beck, C. Allison, L. Morgado, J. Pirker, F. Khosmood, J. Richter, and C. Gütl, Eds., Cham: Springer International Publishing, 2017, pp. 129–141.

[198] William Guest, Fridolin Wild, Alla Vovk, Paul Lefrere, Roland Klemke, Mikhail Fominykh, and Timo Kuula, "A Technology Acceptance Model for Augmented Reality and Wearable Technologies," *Journal of Universal Computer Science*, vol. 24, no. 2, pp. 192–219, 2018, doi: 10.3217/jucs-024-02-0192.

[199] S. Franke, A. Eckstaller, T. Heitland, T. Schaefer, and J. Asseng, "The role of Antarctic overwintering teams and their significance for German polar research," *Polarforschung*, vol. 90, no. 2, pp. 65–79, 2022, doi: 10.5194/polf-90-65-2022.

[200] V. Maiwald, K. Kyunghwan, V. Vrakking, and C. Zeidler, "From Antarctic prototype to ground test demonstrator for a lunar greenhouse," *Acta Astronautica*, vol. 212, pp. 246–260, 2023, doi: 10.1016/j.actaastro.2023.08.012.

[201] M. Eswaran and M. V. A. R. Bahubalendruni, "Challenges and opportunities on AR/VR technologies for manufacturing systems in the context of industry 4.0: A state of the art review," *Journal of Manufacturing Systems*, vol. 65, pp. 260–278, 2022, doi: 10.1016/j.jmsy.2022.09.016.

[202] G. E. Moore, "Cramming More Components onto Integrated Circuits," *Electronics*, vol. 38, no. 8, pp. 114–117, 1965.

[203] J. Shalf, "The future of computing beyond Moore's Law," *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, vol. 378, no. 2166, 2020, doi: 10.1098/rsta.2019.0061.

[204] T. Kozai, G. Niu, and M. Takagaki, Eds., *Plant factory: An indoor vertical farming system for efficient quality food production*. London, San Diego, Cambridge, Oxford: Elsevier Academic Press, 2020.

Appendix

Appendix A: Typical Workdays of the RST 2019 and the OOT 2019

Table A.1: Greenhouse crew time (CT) data for typical workdays of the remote support team 2019.

Day A – 29.05.2019			Day B – 30.07.2019			Day C – 12.08.2019		
Task	**Total Duration [CM-h]**	**People involved**	**Task**	**Total Duration [CM-h]**	**People involved**	**Task**	**Total Duration [CM-h]**	**People involved**
Nominal support (germination, preparation of procedures and checklists)	1.25	1	Housekeeping	0.50	1	Housekeeping	0.50	1
			Preparation of weekly meeting	0.50	1	Organizing next mission	1.00	1
			Nominal meeting (weekly/bi-weekly)	4.00	4	Off-nominal support (broken high-pressure pump)	3.00	1
Daily Total CT	**1.25**		**Daily Total CT**	**5.00**		**Daily Total CT**	**4.50**	

Table A.2: Greenhouse crew time (CT) data for typical workdays of the on-site operator team 2019.

Day A – 28.06.2019			Day B – 30.07.2019			Day C – 12.08.2019		
Task	**Total Duration [CM-h]**	**People involved**	**Task**	**Total Duration [CM-h]**	**People involved**	**Task**	**Total Duration [CM-h]**	**People involved**
Daily check; Harvesting lettuce; Cleaning trays; Cucumber training	4.00	2	Nominal meeting (weekly/bi-weekly)	2.00	2	Off-nominal event (investigating reason behind alarms)	5.00	2
Filling up fresh water 80 l	1.00	1	Daily check; Harvesting rucola, lettuce, cucumber; Cleaning trays; Tomato training	2.00	2			
Daily Total CT	**5.00**		**Daily Total CT**	**4.00**		**Daily Total CT**	**5.00**	

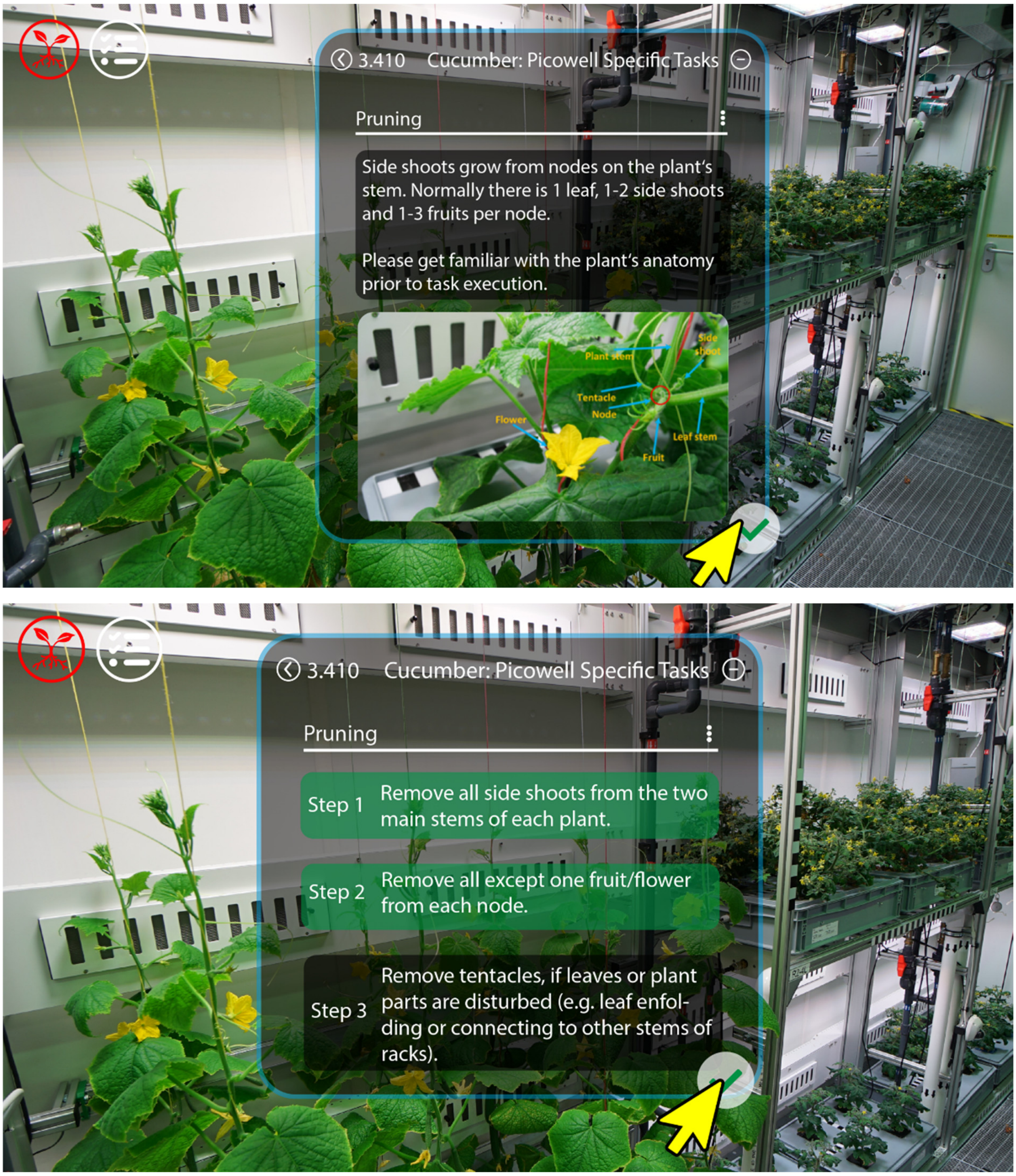
Appendix B: Possible Application Areas and Exemplary Functions for AR Use in a Planetary Surface Greenhouse

Table B.1: Possible application areas and exemplary functions for augmented reality use in a planetary surface greenhouse. Reproduced and modified from Zeidler and Woeckner [146].

Possible Application Areas	Exemplary Functions
1. Display of technical greenhouse information	• Sensor data, e.g., temperature, relative humidity, CO_2-level, light settings • Actuator data, e.g., pressure/temperatures in tubes or pumps, system active or inactive • Handling of alarms in greenhouses • Localization tool to locate items faster in the greenhouse (e.g., alarm/task locations, tools, sensors/actuators or control elements) by using 3D models
2. Display of plant-specific information	• Plant data, e.g., seeding time and location, transplanting time or cultivar/variety • Real-time plant health monitoring system, e.g., display of plant health status
3. Display of planning tools	• Operation procedures for tasks performed in the greenhouse, e.g., tending plants, maintenance work or repair tasks • Daily planning tool • Automatic crop planning tool to calculate the optimal time and location for seeding, transplanting and harvesting to generate continuous output
4. Communication tool	• Support of tele-operation tasks, e.g., document sharing, video conferencing • Share view of operator in greenhouse with the support team on ground (capability to draw annotations, e.g., circles, arrows or text within the user's field of vision) • Remote assistance: two-way voice and video communication to the mission control center for faster troubleshooting in case of emergency or repairs
5. Document processing functions	• Share, edit or view documents • Progress marker to visualize the support team on ground which operation is being processed and which step is being performed by the operator • Taking notes

Appendix C: Exemplary Images of ARCHIE^2 AR Interface Functionalities

Figure C.1: Concept of the menu and submenus of the ARCHIE^2 augmented reality interface used inside the EDEN ISS greenhouse in Antarctica: ***(A)*** *Home Screen and Tasks menu;* ***(B)*** *Greenhouse Environment submenu;* ***(C)*** *Communication submenu;* ***(D)*** *Plant Environment mode turned on. The yellow mouse pointer only illustrates a selection action on the interface (not part of the prototype). [91] Photo credits: Hanno Müller.*



3.410 Cucumber: Picowell Specific Tasks

Pruning

Side shoots grow from nodes on the plant's stem. Normally there is 1 leaf, 1-2 side shoots and 1-3 fruits per node.

Please get familiar with the plant's anatomy prior to task execution.

3.410 Cucumber: Picowell Specific Tasks

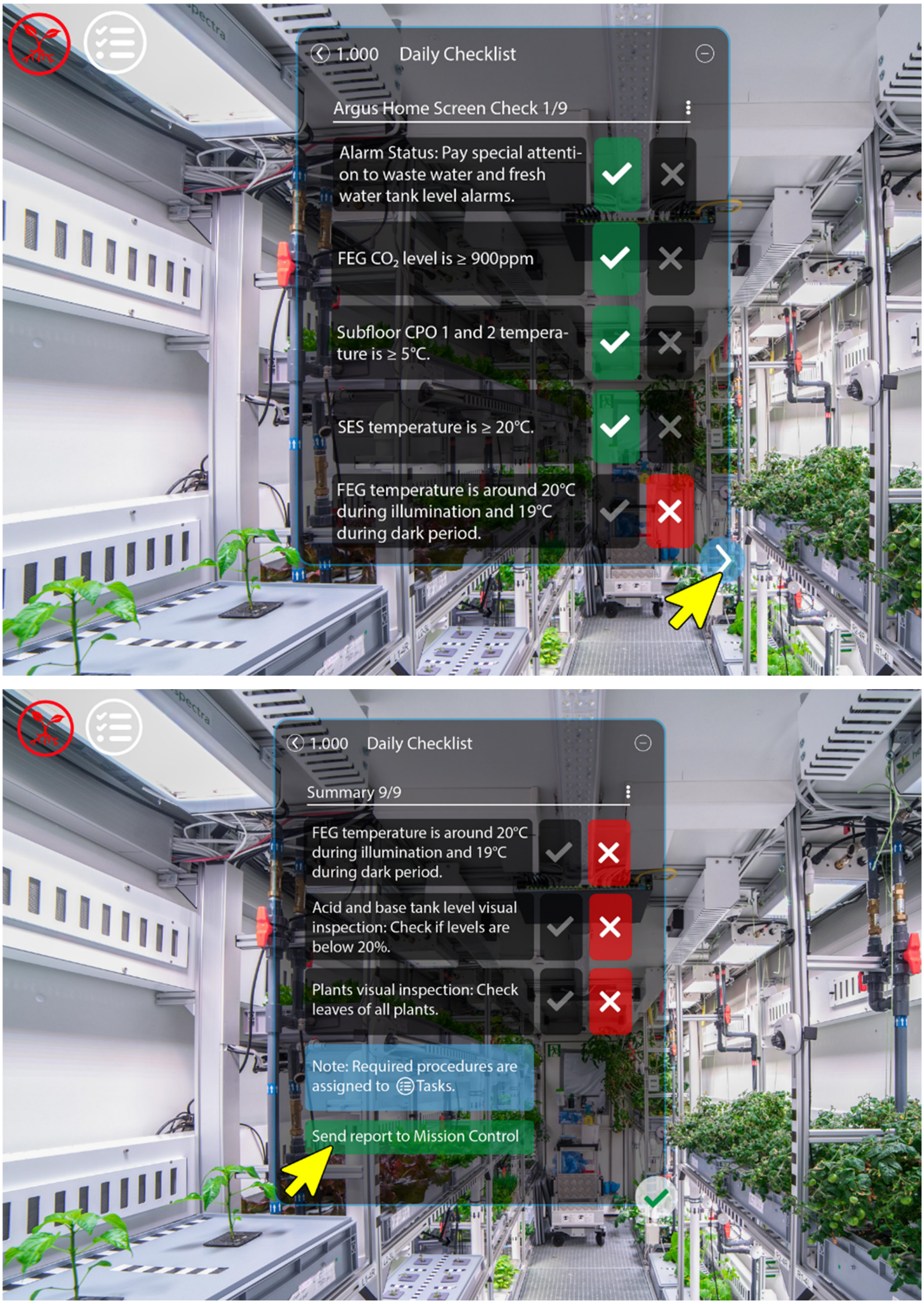
Pruning

Step 1 Remove all side shoots from the two main stems of each plant.

Step 2 Remove all except one fruit/flower from each node.

Step 3 Remove tentacles, if leaves or plant parts are disturbed (e.g. leaf enfolding or connecting to other stems of racks).

Figure C.2: Concept of a cucumber pruning task procedure visualization using the ARCHIE² augmented reality interface inside a greenhouse with step-by-step explanations. The yellow mouse pointer only illustrates a selection action on the interface (not part of the prototype). [91] Photo credits: Paul Zabel.



Alarm Status: Pay special attention to waste water and fresh water tank level alarms.

FEG CO_2 level is ≥ 900ppm

Subfloor CPO 1 and 2 temperature is ≥ 5°C.

SES temperature is ≥ 20°C.

FEG temperature is around 20°C during illumination and 19°C during dark period.

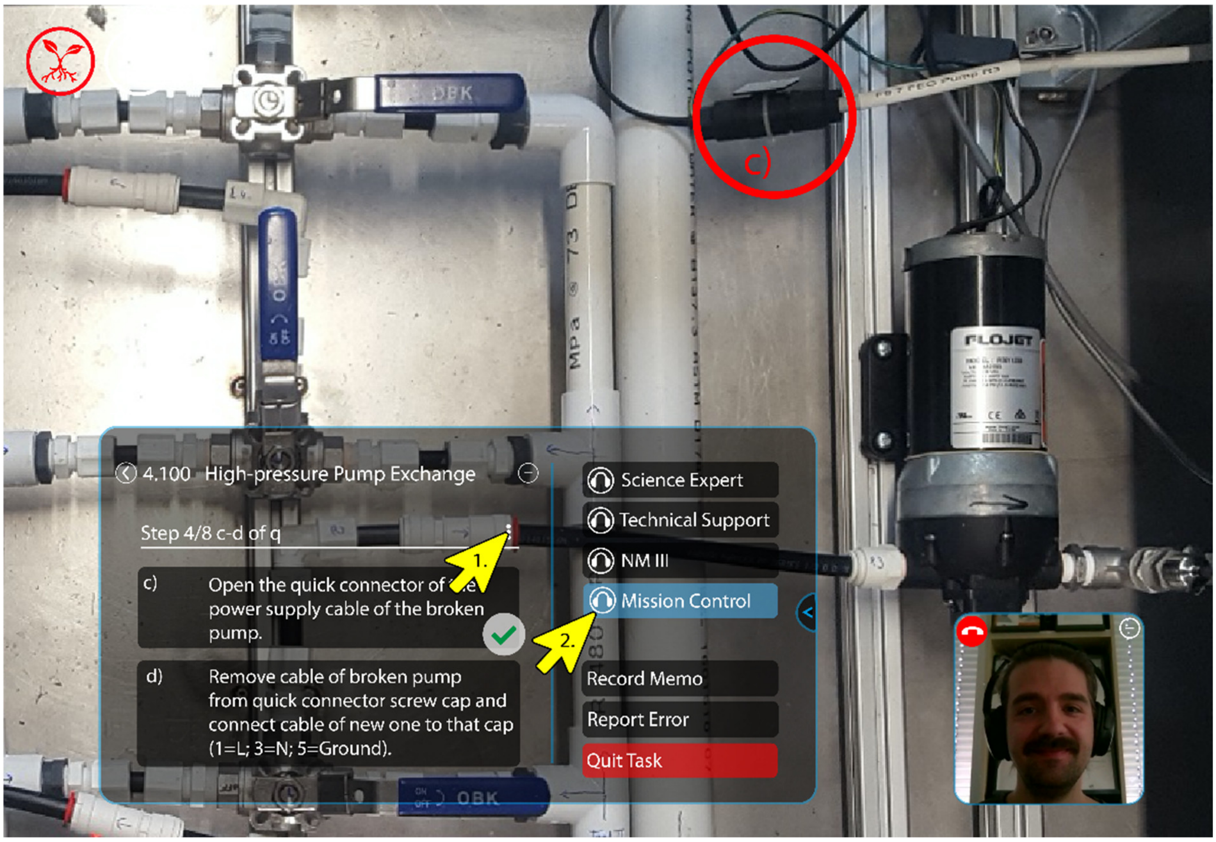
FEG temperature is around 20°C during illumination and 19°C during dark period.

Acid and base tank level visual inspection: Check if levels are below 20%.

Plants visual inspection: Check leaves of all plants.

Note: Required procedures are assigned to Tasks.

Figure C.3: Concept of a daily checklist visualization using the ARCHIE^2 augmented reality interface inside a greenhouse. The yellow mouse pointer only illustrates a selection action on the interface (not part of the prototype). [91] Photo credits: Hanno Müller.



4.100 High-pressure Pump Exchange

Step 4/8 c-d of q

c) Open the quick connector of the power supply cable of the broken pump.

d) Remove cable of broken pump from quick connector screw cap and connect cable of new one to that cap (1=L; 3=N; 5=Ground).

Figure C.4: Concept of an exemplary remote support situation of the on-site operator while exchanging a high-pressure pump in the greenhouse using the ARCHIE^2 augmented reality interface. The red circle was drawn by the remote support expert to illustrate where the power cable must be disconnected. The yellow mouse pointer only illustrates a selection action on the interface (not part of the prototype). [91] Photo credits: Paul Zabel.

Appendix D: Composition of the Datasets and Evaluation of the Training Results

Dataset D1

(Only one class was used: arugula selvatica class)

Table D.1: Composition of dataset D1 to train the model for arugula selvatica detection. [a] Images without arugula selvatica are from various perspectives. [177]

Source of Images	Content of Images	Number of Images	Number of Annotated Instances
EDEN ISS Greenhouse	Top-view with arugula	310	5,280
	Without arugula [a]	40	0
External	Various	83	135
Total		**433**	**5,415**

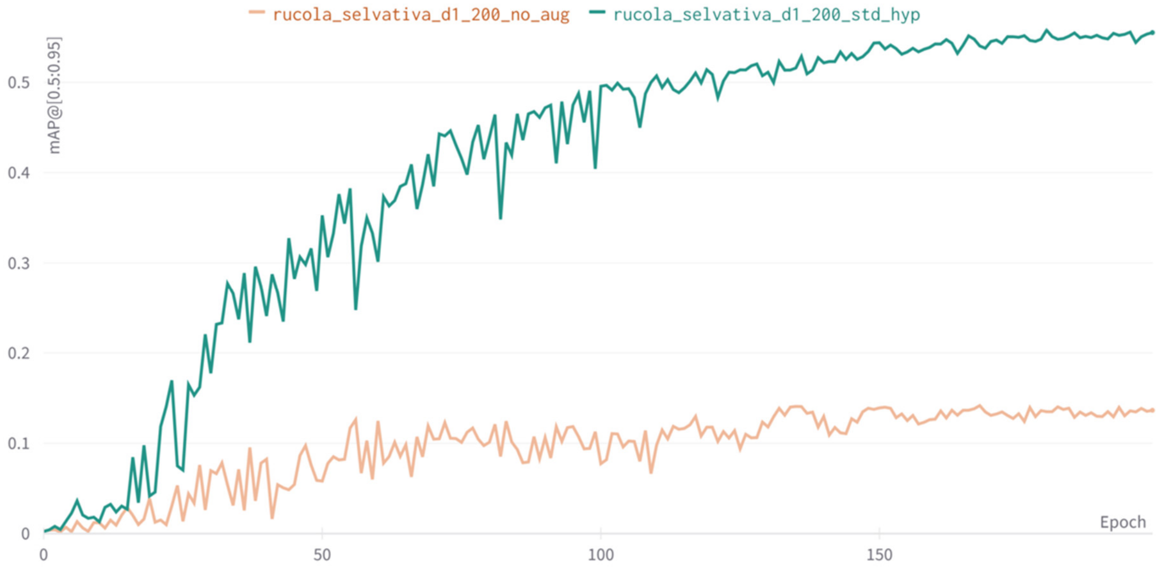


Figure D.1: Course of the mAP@[0.5:0.95] over the training run of dataset D1 on the validation set with augmentation (green) and without augmentation (orange). [177]

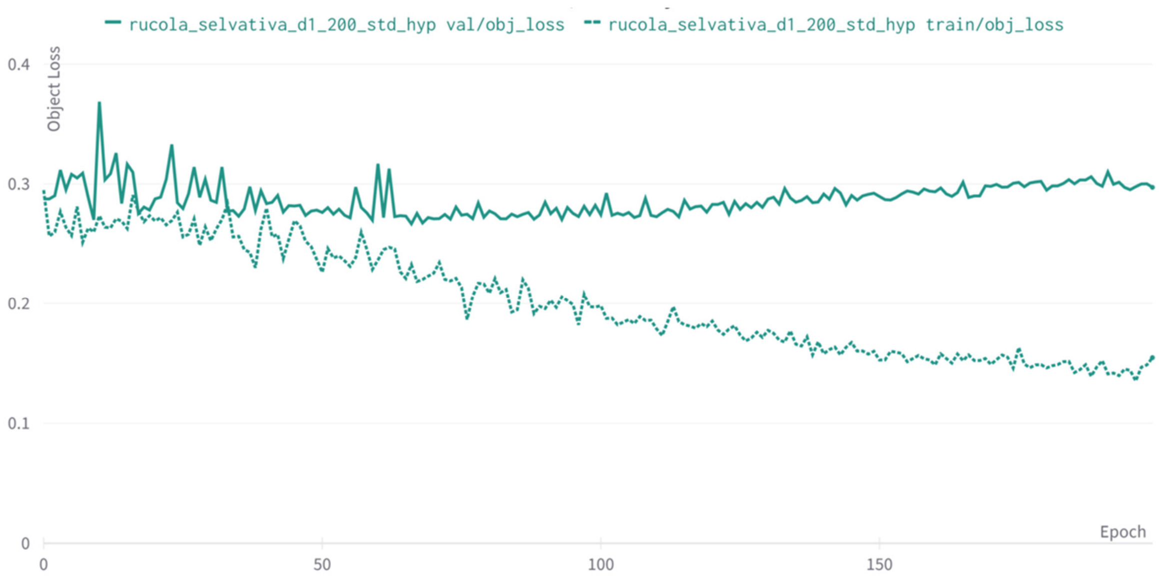


Figure D.2: Course of the object loss over the training run of dataset D1 with augmentation on the validation set (continuous) and training set (dashed). [177]

Figure D.3: Course of the box loss over the training run of dataset D1 with augmentation on the validation set (continuous) and training set (dashed). [177]

Dataset D2

(Only one class was used: arugula selvatica class)

Table D.2: Composition of dataset D2 to train the model for arugula selvatica detection. [a] Images without arugula selvatica are from various perspectives. [177]

Source of Images	Content of Images	Number of Images	Number of Annotated Instances
EDEN ISS Greenhouse	Top-view with arugula	618	10,534
	Without arugula [a]	67	0
External	Various	82	134
Total		**767**	**10,668**

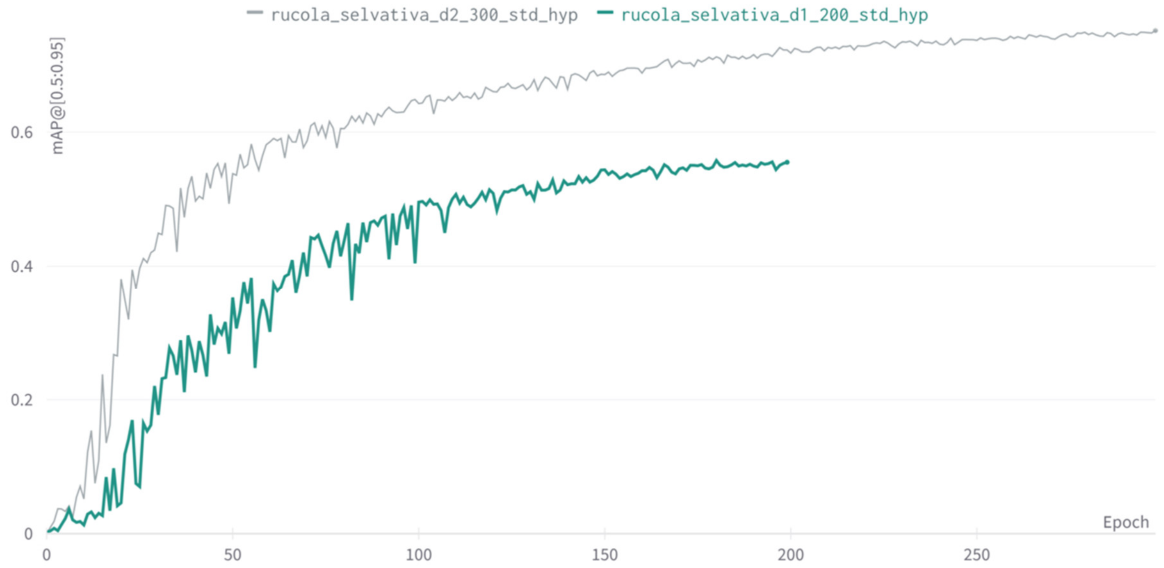


Figure D.4: Course of the mAP@[0.5:0.95] over the training run of dataset D1 on the validation set with augmentation (green) and dataset D2 on the validation set (grey). [177]

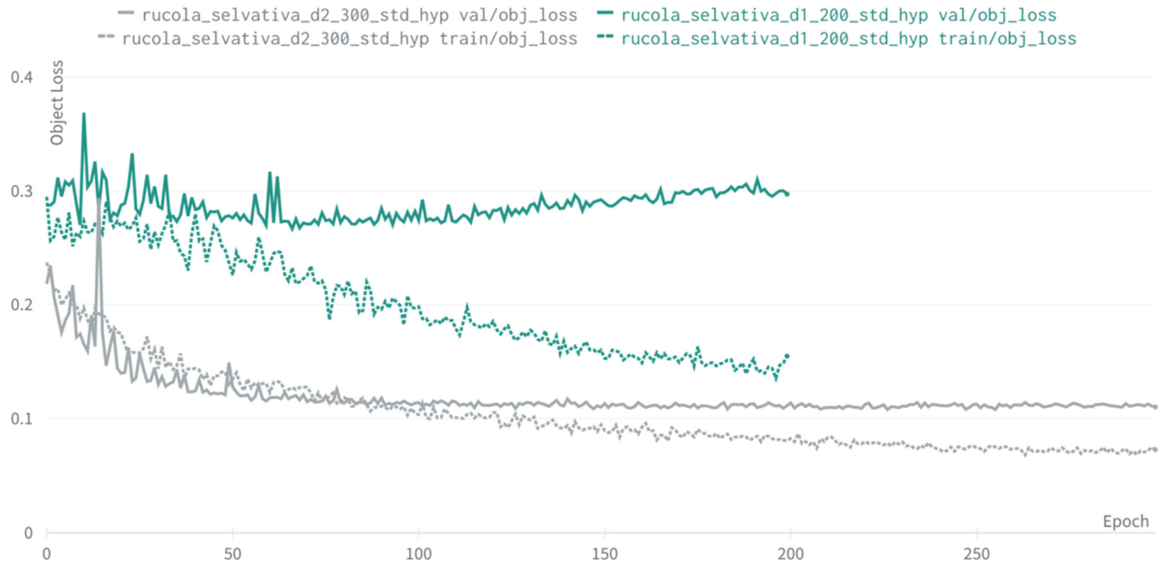


Figure D.5: Course of the object loss over the training run of dataset D1 with augmentation (green) and dataset D2 (grey) on the validation set (continuous) and training set (dashed). [177]

Dataset D3

(Only one class was used: arugula selvatica class)

Table D.3: Composition of dataset D3 to train the model for arugula selvatica detection. [a] Images without arugula selvatica are from various perspectives. [177]

Source of Images	Content of Images	Number of Images	Number of Annotated Instances
EDEN ISS Greenhouse	Top-view with arugula	618	10,534
	Side-view with arugula	334	591
	Without arugula [a]	67	0
External	Various	82	134
Total		**1,101**	**11,259**

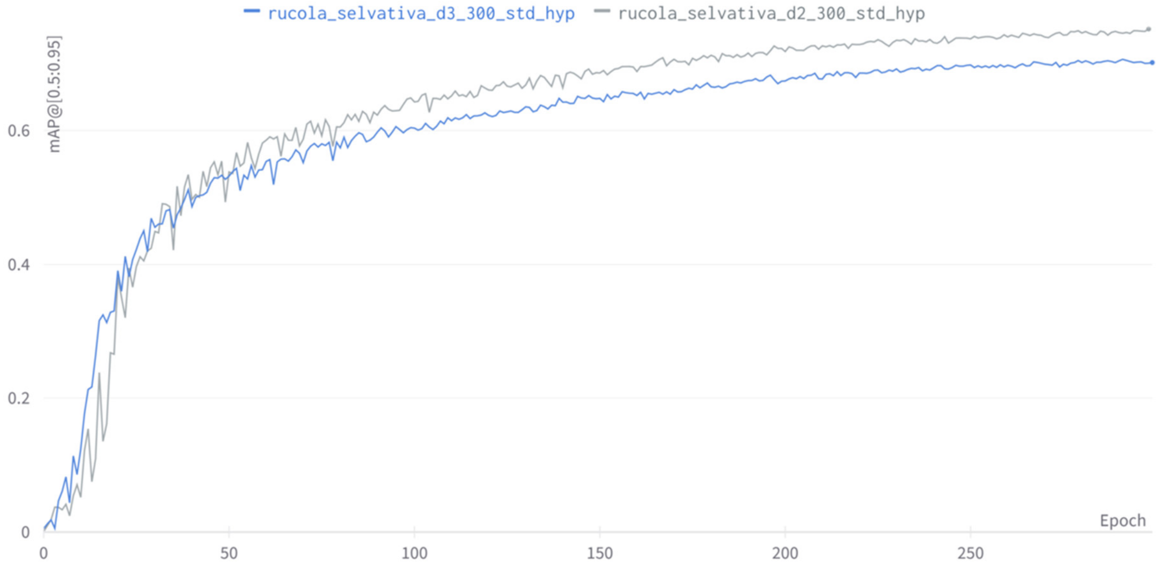


Figure D.6: Course of the mAP@[0.5:0.95] over the training run of dataset D2 on the validation set (grey) and dataset D3 on the validation set (blue). [177]

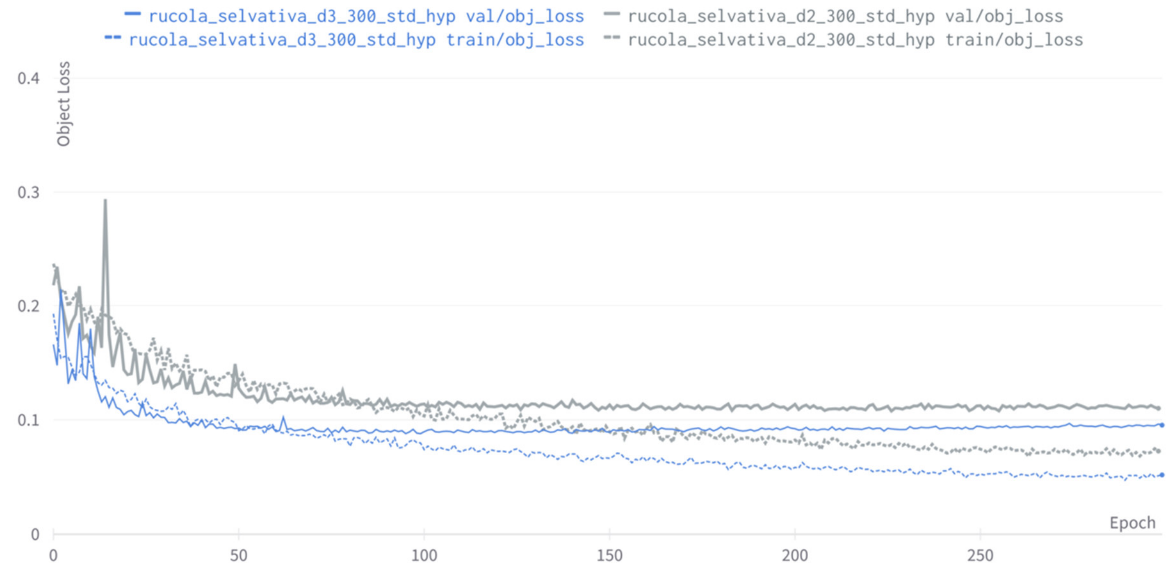


Figure D.7: Course of the object loss over the training run of dataset D2 (grey) and dataset D3 (blue) on the validation set (continuous) and training set (dashed). [177]

Dataset D4 and Dataset D5

(Two classes were used: arugula selvatica class and arugula selvatica batch class)

Table D.4: Composition of dataset D4 to train the model for arugula selvatica detection. [a] Images without arugula selvatica are from various perspectives. [177]

Source of Images	Content of Images	Number of Images	Number of Annotated Instances
EDEN ISS Greenhouse	Top-view with arugula	618	10,534
	Side-view with arugula	334	591
	Without arugula [a]	67	0
External	Various	82	134
Total		**1,101**	**11,259**

Table D.5: Composition of dataset D5 to train the model for arugula selvatica detection. [a] Images without arugula selvatica are from various perspectives. [177]

Source of Images	Content of Images	Number of Images	Number of Annotated Instances
EDEN ISS Greenhouse	Top-view with arugula	618	10,510
	Side-view with arugula	668	1,182
	Without arugula [a]	57	0
External	Various	67	110
Total		**1,410**	**11,802**

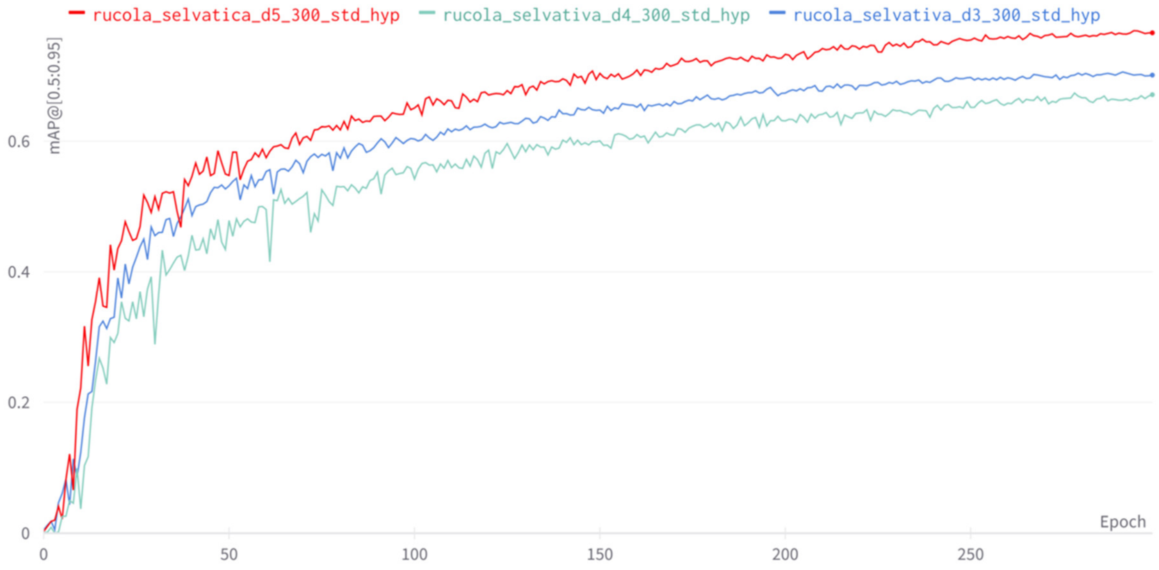


Figure D.8: Course of the mAP@[0.5:0.95] over the training run of dataset D3 on the validation set (blue), dataset D4 on the validation set (green) and dataset D5 on the validation set (red). [177]

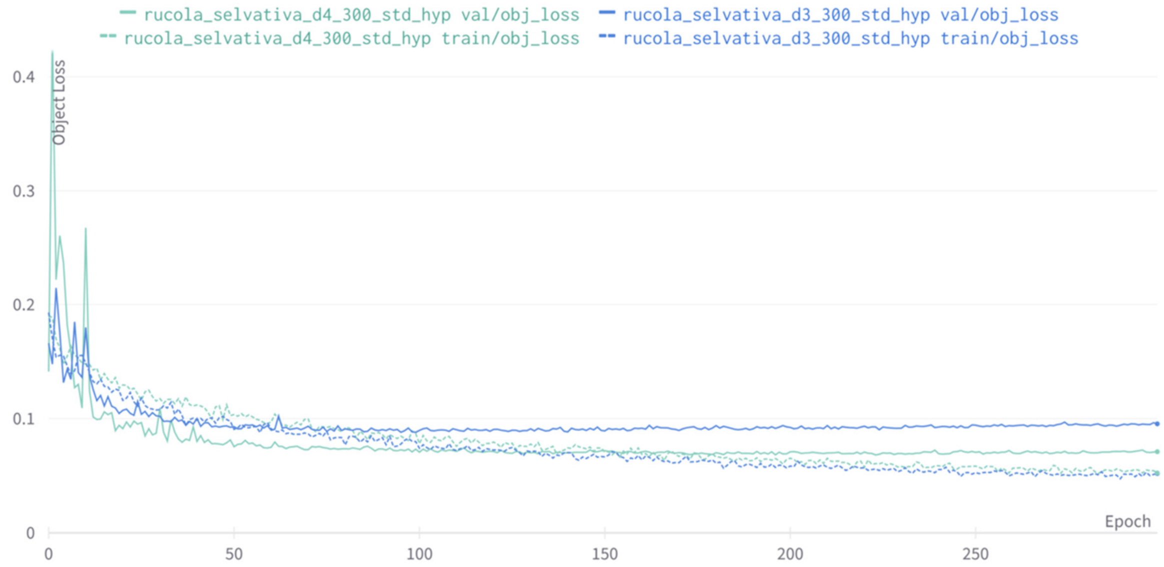


Figure D.9: Course of the object loss over the training run of dataset D3 (blue) and dataset D4 (green) on the validation set (continuous) and training set (dashed). [177]

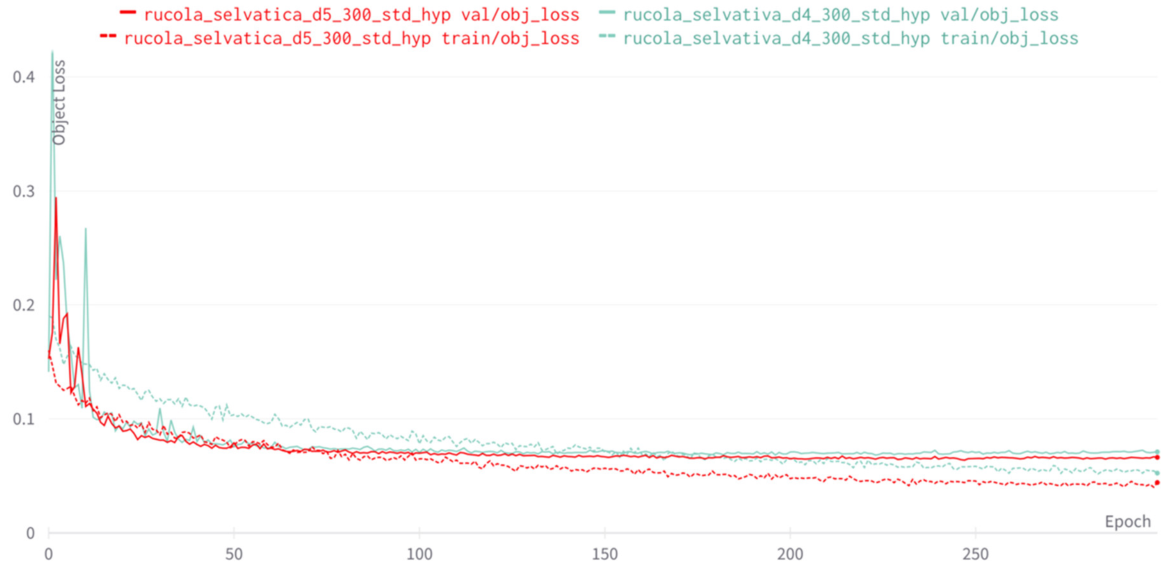


Figure D.10: Course of the object loss over the training run of dataset D4 (green) and dataset D5 (red) on the validation set (continuous) and training set (dashed). [177]

Dataset 6

(Only one class was used: arugula selvatica class)

Table D.6: Composition of dataset D6 to train the model for arugula selvatica detection. [a] Images without arugula selvatica are from various perspectives. [177]

Source of Images	Content of Images	Number of Images	Number of Annotated Instances
EDEN ISS Greenhouse	Top-view with arugula	618	10,510
	Side-view with arugula	668	1,182
	Without arugula [a]	57	0
External	Various	67	110
Total		**1,410**	**11,802**

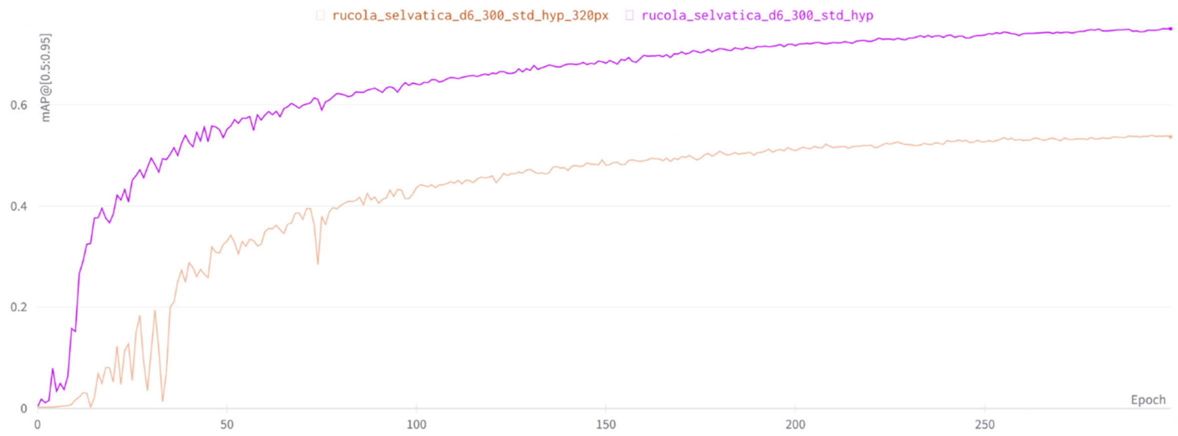


Figure D.11: Course of the mAP@[0.5:0.95] over the training run of dataset D6 on the validation set with 1,920 px (purple) and 320 px (orange). [177]

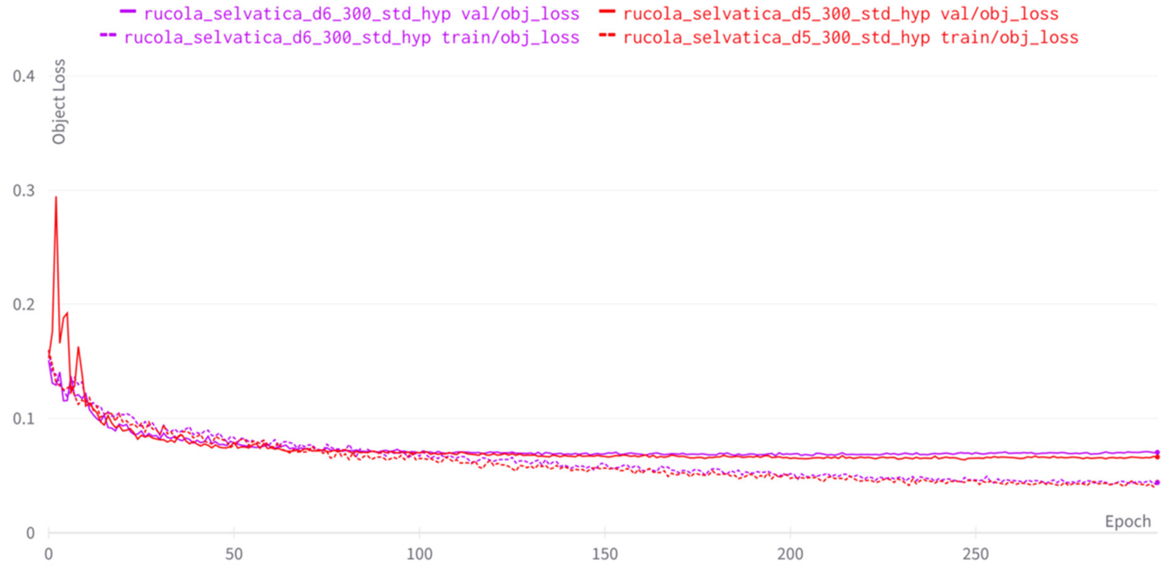


Figure D.12: Course of the object loss over the training run of dataset D5 (red) and dataset D6 (purple) on the validation set (continuous) and training set (dashed). [177]

Summary of Metrics Achieved through Training for Arugula Selvatica Detection

Table D.7: Summary of metrics achieved through training for arugula selvatica detection on datasets D1 to D7. Improvements in values compared to the previous dataset are highlighted in green and degradations in red. D7 is the selected model for deployment on the HoloLens 2. [a] Dataset is without YOLOv5 standard augmentation. Reproduced and modified from Klug [177].

Dataset	Configuration of Runs			mAP @[0.5:0.95]	Training-/ Validation-Set Object Loss	Training-/ Validation-Set Box Loss
	Image Size	Batch Size	Epochs			
D1 [a]	2,688 px	4	200	0.1365	0.0149/ 0.5933	0.0099/ 0.0711
D1	2,688 px	4	200	0.5551	0.1547/ 0.2972	0.0216/ 0.0356
D2	1,920 px	8	300	0.7515	0.0728/ 0.1101	0.0156/ 0.0231
D3	1,920 px	8	300	0.7014	0.0519/ 0.0954	0.0138/ 0.0240
D4	1,920 px	8	300	0.6714	0.0525/ 0.0711	0.0151/ 0.0236
D5	1,920 px	8	300	0.7661	0.0442/ 0.0663	0.0149/ 0.0160
D6	1,920 px	8	300	0.7506	0.0439/ 0.0703	0.0152/ 0.0163
D7	**320×192 px**	**8**	**300**	**0.5368**	**0.04202/ 0.03879**	**0.04839/ 0.04965**