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Crew time and workload in the EDEN ISS greenhouse in Antarctica

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ABSTRACT

The goal of the EDEN ISS project is to research technologies for future greenhouses as a substantial part of planetary surface habitats. In this paper, we investigate crew time and workload needed to operate the space analogue EDEN ISS greenhouse on-site and remotely from the Mission Control Center. Within the almost three years of operation in Antarctica, different vegetable crops were cultivated, which yielded an edible biomass of 646 kg during the experiment phase 2018 and 2019.

Operating in such a remote environment, analogue to future planetary missions, both greenhouse systems and remote support capabilities must be carefully developed and assessed to guarantee a reliable and efficient workflow. The investigation of crew time and workload is crucial to optimize processes within the operation of the greenhouse. For the Antarctic winter seasons, 2019 and 2020, as well as the summer season 2019/2020, the workload of the EDEN ISS greenhouse operators was assessed using the NASA Task Load Index. In addition, crew time was measured for the winter season 2019.

The participants consisted of on-site operators, who worked inside the EDEN ISS greenhouse in Antarctica and the DLR remote support team, who worked in the Mission Control Center at the DLR Institute of Space Systems in Bremen (Germany).

The crew time results show that crew time for the whole experiment phase 2019 required by the on-site operator team 2019 is approximately four times higher than the crew time of the corresponding remote support team without considering planning activities for the next mission. The total crew time for the experiment phase 2019 amounts to 694.5 CM-h or 6.31 CM-h/kg. With the measurements of the experiment phase 2019 it was possible to develop a methodology for crew time categorization for the remote support activities, which facilitates the analysis and increases the comparability of crew time values. In addition, the development of weekly and monthly crew time demand over the experiment phase is presented.

The workload investigations indicate that the highest workload is perceived by the remote support team 2019 + 2020, followed by the summer maintenance team 2019/2020. The on-site operator team 2019 and on-site operator team 2020 showed the lowest values. The values presented in this paper indicate the need to minimize crew time as well as workload demands of the operators involved in the operation of future planetary surface greenhouses.

1. Introduction

During long-term space missions it is necessary to address the serious problem of a lack of certain nutrients and vitamins (Smith et al., 2005; Douglas et al., 2016; Cooper et al., 2017). The cultivation of higher plants during planetary surface missions will help to produce oxygen, reduce carbon dioxide, manage waste products and recycle water (Wheeler 2010). 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 (Bates et al., 2009; Bringslimark et al., 2009; Odeh, Guy 2017) and the

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Nomenclature

AWI	Alfred-Wegener-Institute
CM-h	Crew Member-hour
CM-min	Crew Member-minutes
CPO	Cold Porch
CT	Crew Time
DLR	German Aerospace Center
ECLSS	Environmental Control and Life Support System
FEG	Future Exploration Greenhouse
HI-SEAS	Hawaii Space Exploration and Analog Simulation
ISS	International Space Station
MCC	Mission Control Center
MDRS	Mars Desert Research Station
MRE	Meals Ready to Eat
MTF	EDEN ISS Mobile Test Facility
NDS	Nutrient Delivery System
NM III	Neumayer Station III
OOT	On-site Operator Team
RST	Remote Support Team
SEM	Standard Error of the Mean
SES	Service Section
SMT	On-site Summer Maintenance Team
SPFGC	South Pole Food Growth Chamber
TCS	Thermal Control System
TLX	NASA Task Load Index
WL	Workload

consumption of fresh vegetables is beneficial to the physical and psychological health of the crew (Australian Antarctic Division 1994; Berkovich et al., 2009; Głąbska et al., 2020).

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 test-beds include NASA's Biomass Production Chamber (Wheeler et al., 2003), the Lunar Greenhouse (Sadler et al., 2011), the South Pole Food Growth Chamber (Patterson et al., 2012), the Arthur Clarke Mars Greenhouse in the Canadian high Arctic (Bamsey et al., 2009), the series of BIOS projects (Salisbury et al., 1997), or the Lunar Palace (Fu et al., 2016).

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 (Zabel et al., 2016; Schubert et al., 2018; Zabel, Zeidler 2019; Vrakking et al., 2020b). The greenhouse, called Mobile Test Facility (MTF), was installed near the Neumayer III Antarctic Research Station (NM III, 70°40S, 8°16W), which is operated by the Alfred-Wegener-Institute for Polar and Marine Research (AWI) (Gernandt et al., 2007; Wesche et al., 2016). The greenhouse is operated by at least one on-site operator, who is part of the NM III wintering crew, with support from the Mission Control Center (MCC) at the German Aerospace Center (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 analogue 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. (Bamsey et al., 2014; Zabel, Zeidler 2019) 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 for the whole research station (Kohlberg et al., 2017). Another similarity between the NM III wintering crew and future astronauts is the importance of crew time (CT) utilization. A significant fraction of the wintering crew's CT is required for scientific activities, so the CT effort to maintain NM III as well as the EDEN ISS greenhouse should be minimized as much as possible.

The first contribution of this paper is to provide detailed CT estimates for the experiment phase 2019 (April to November). The objective is to add relevant CT data, associated with the corresponding edible biomass production, to the field of research while providing insights into the CT demand of the on-site operator team (OOT) for the EDEN ISS space analogue greenhouse and the CT[1] demand of the remote support team (RST) in the MCC. In addition, the development of CT of the two teams and the CT distribution between the two teams over the course of the experiment phase 2019 is analyzed. Derived from the measured CT values for the RST 2019, a methodology is presented to categorize the CT needed for remote support. The second contribution is to provide an assessment of workload (WL) regarding the operational activities related to a space analogue greenhouse. To achieve this, the WL of the OOTs during the experiment phases in winter season 2019 and 2020, of the on-site summer maintenance team (SMT) during the summer season 2019/2020, as well as of the RSTs during the experiment phases 2019 and 2020, is assessed using the NASA Task Load Index (TLX) questionnaire. Based on the results of the TLX, possible solutions for WL optimizations are proposed. The final key contribution is the examination of the CT impact and the WL investigation results for the planning and operation processes of future planetary surface missions with greenhouses incorporated into the habitat infrastructure.

2. Related work

2.1. Crew time and workload in space missions

Efficient use of CT is key for the scientific success of space missions. CT is a limited and expensive resource on a space mission (National Research Council 2003; Stromgren et al., 2018). The current pricing policy rate to support commercial/marketing activities on the International Space Station (ISS) is 130,000 $ per hour (NASA 2019). For planetary surface missions these costs will increase further. Consequently, CT has to be minimized as much as possible (Eckart 1996; Bamsey et al., 2009).

Furthermore, Coleshill et al. (2009) 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 (National Research Council 2003). According to Russell et al. (2006), CT needed for scheduled and unscheduled maintenance of the Environmental Control and Life Support System (ECLSS) onboard the ISS was 13 to 15 times higher than the CT value of 50.0 CM-h per year (1.0 CM-h per week) estimated during the design process. In addition, on

[1] The term crew time is normally applied for astronaut crews and not for 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 paper 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.

Skylab, 0.75 CM-h per crew member per day were considered for housekeeping tasks, but the actual average value was 1.1 CM-h per crew member per day. Also, on Mir CT for unscheduled maintenance tasks was higher than planned, while other activities such as sleep were reduced to be able to accomplish additional maintenance tasks (Russell et al., 2006). As a consequence, this could have a negative effect on the crew's psychological well-being (Mattfeld et al., 2015) and can consequently endanger the outcome of a space mission. As seen, actual required CT generally exceeded the planned CT in past space missions due to higher amounts of scheduled maintenance and unexpected tasks, so more knowledge and effort is required to define and assess CT needs for future space missions (Russell et al., 2006).

Aside from CT, also perceived WL is of interest for 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 CT data and WL measurements, especially for the operation time of planetary surface greenhouses, which is heavily needed for planning.

2.1.1. International Space Station

There are publications regarding CT investigations for the ISS, but none of them are related to plant cultivation activities Russell et al. (2006); Mattfeld et al., (2015) and Anderson et al., (2015), for example, reported CT values for a typical workday of the crew onboard the ISS. The astronauts on ISS work approximately 8.5 CM-h per weekday and 0.3 CM-h per day on weekends with eight days of vacation per crew member per year (Anderson et al., 2015). One week consists of five weekdays and two days of weekend.

There is some overlap in the categorization of CT in the literature. Nevertheless, as there is often only partial overlap, it makes it difficult to compare the CT values for specific tasks. In Stromgren et al., (2018) a methodology is presented for CT categorization divided into work and non-work activities for the ISS, which was also used in Mattfeld et al., (2015). Stromgren et al., (2018) subdivides these categories into sub-categories, activities, sub-activities and operation type. This simplified methodology of Stromgren et al., (2018) can help to compare the values of various publications in the future. Furthermore, some CT values for specific ISS tasks are shown and adjusted with respect to future Gateway missions.

Mattfeld et al., (2015) discusses a CT model for a crewed Mars mission and discusses potential utilization time for science activities. But as mentioned previously, there are no tasks presented related to planetary surface greenhouses. For example, the time needed for meals (12.25 CM-h per week) and preparation (2 CM-h per week) accounts to 14.25 CM-h per week for a Mars surface mission. These numbers solely consider the use of the meals ready to eat (MRE) without the cultivation of plants in a greenhouse, which would add additional CT for such missions and would result in the need to reduce CT for other tasks presented in Mattfeld et al., (2015) such as for example public relations or pre/ post sleep.

2.1.2. Planetary surface analogue greenhouses on Earth

Nevertheless, there is also literature with CT values for work in planetary surface analogue greenhouses on Earth. As reported by Schwartzkopf (1991) as well as Eckart (1996) 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 test bed. CT was measured in CM-h/d*m^2 for plant related tasks like planting, harvesting, wheat grinding, observation, preventive maintenance and nutrient solution maintenance (Schwartzkopf 1991; Eckart 1996).

Another example of a planetary surface analogue greenhouse is the Mars-Lunar Greenhouse (Sadler et al., 2011). 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 (Sadler et al., 2011).

Patterson et al., (2012) 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 South Pole Food Growth Chamber (SPFGC). The CT for the various tasks of the SPFGC operator was tracked and divided into three categories: a) daily, such as checking the computer and data acquisition system or watering seedlings, accounted to 1.6 CM-h per day, b) weekly, such as harvesting or seeding, to 1.5 CM-h per day and c) monthly, such as filling and mixing concentrated stock solutions, to 0.2 CM-h per day. A total of 23 CM-h per week of CT was needed by the operator to maintain the SPFGC (Patterson et al., 2012), but not all CT 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 CT of the volunteers was not included in the measurements (Patterson 2011). Also, the CT for maintenance and repair activities for the primary hardware systems was not included (Patterson et al., 2012).

Zabel et al., (2019) investigated the CT for different crop species as well as complete workdays for the experiment phase 2018 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., (2019), the various types of tasks conducted in a planetary surface greenhouse can be divided into four categories: crop cultivation, maintenance, repair and science. The CT required to maintain the system is higher than the CT required for the plant care. Another finding of Zabel et al., (2019) was the fact that each crop species requires a different number of tasks to be performed and, consequently, requires varying amounts of CT during cultivation, so it is important to choose the most suitable crop for a space mission. This statement is also supported by Schwartzkopf (1991). In light of this, Zabel et al., (2019) 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 CT. Indeed, even though radish plants grow very fast, their CT demand for harvest is higher because they are multiple single plants and their tuber needs to be separated from the leaves. Additionally, the CT for the 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 (Zabel et al., 2019).

There are also space analogue test sites whose primary scientific focus is not plant cultivation but which include plant growth facilities on their premises such as the Hawaii Space Exploration and Analog Simulation (HI-SEAS) missions or the Mars Desert Research Station (MDRS) missions.

From March to June 2014, a 120-day simulation of a mission on Mars was conducted at the HI-SEAS analogue test site. (Poulet et al., 2014) During that period, lettuces (2 × 27 days) and radishes (2 × 20 days) were cultivated on plant trays under LED lighting in a semi-controlled environment inside the habitat. Besides the lighting investigations, CT for plant cultivation operations such as watering, temperature checking, sowing, or harvesting were measured and reported per task and as total values. (Poulet et al., 2014)

Since 2002, as described by Poulet and Doule (2014), a greenhouse module with a growth area of 5 m^2, called GreenHab, has been attached to MDRS via simulated pressurized corridor. CT 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 CT readings in average minutes per day are divided by task, such as watering, covering/uncovering plants or harvesting and finally clustered into daily operations, exceptional operations and maintenance (Poulet and Doule 2014).

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

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 Future Exploration Greenhouse (FEG) container and the Service Section container, which comprises the Service Section (SES) and the Cold Porch (CPO) as can be seen in Fig. 1. (Vrakking et al., 2017; Zabel et al., 2017; Zabel, Zeidler 2019)

The fresh vegetables produced in the MTF on a growth area of 12.5 m^2 are consumed by the wintering crew of the NM III. During the winter season 2019, approximately 110 kg of edible fresh biomass was produced inside the MTF. In Table 1, the monthly edible fresh biomass output is depicted as a sum for all cultivated plants. Table 2 shows all crops cultivated in the MTF during the experiment phase 2019.

3. Crew time and workload recordings within EDEN ISS

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 (Zabel, Zeidler 2019) 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 winter season 2018, 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 of 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 analogue 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 CT, WL and operation processes (Vrakking et al., 2020b).

As depicted in Fig. 2 the cultivation of plants in the greenhouse started in winter season 2019 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 (Vrakking et al., 2020a; Vrakking et al., 2020b), which ended on 06.05.2019 with first activities of the on-site operators inside the facility. The startup of all the

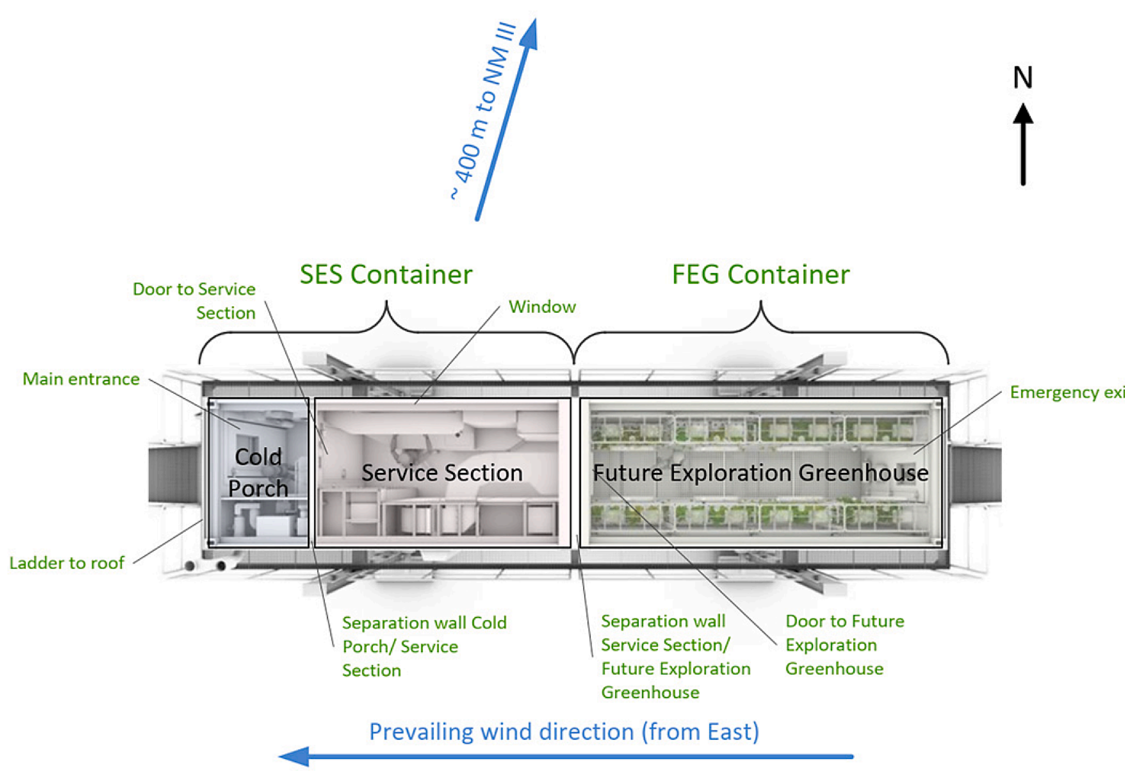

Fig. 1. Overview of the EDEN ISS MTF main elements (Zabel et al., 2016).

Table 1
Monthly fresh edible biomass harvest for all crops grown in the MTF during the experiment phase 2019 as reported in Vrakking et al., 2020b. The values were updated, due to a processing error in Vrakking et al., 2020b.

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 2
List of all crops grown in the MTF during the experiment phase 2019.

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

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 winter season 2020 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 summer season 2019/2020.

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 (Schubert et al., 2018; Zeidler et al., 2019). 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 carry 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 have 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 solve the issue, which is afterwards executed by the OOT. Communication is done via text messages including image transfer, emails, as well as 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 7 and Table 8 in the supplementary material.

3.2. Remote support crew time categorization

To better analyze, understand and visualize the CT 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 CT values of the RST 2019 showed that their tasks could be

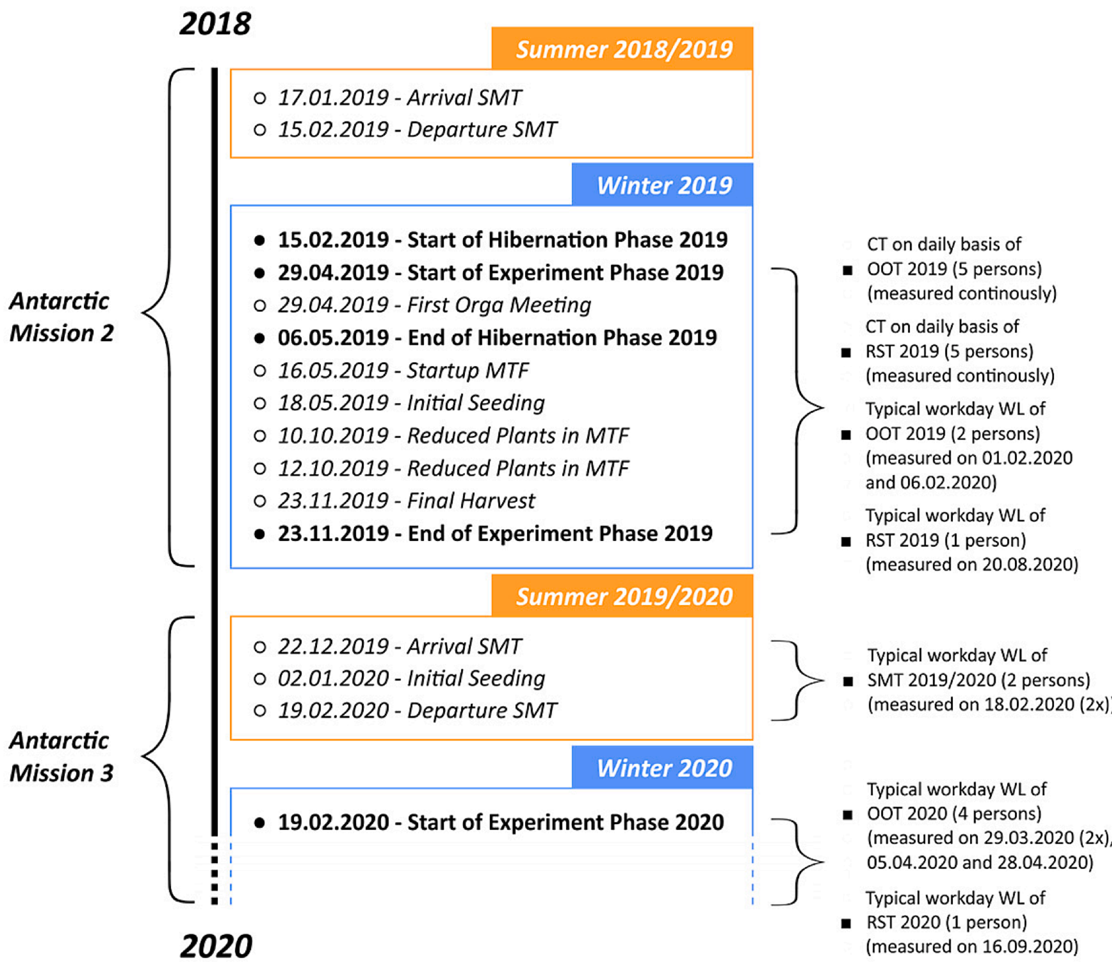

Fig. 2. Overview of the EDEN ISS MTF mission timeline with information about the measurements on the right side (blank bullet points representing specific moments in time; solid bullet points representing start/end points of phases).

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 of the following week and to discuss open questions regarding the operation 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, 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 which 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 of the next summer and winter season at the NM III. This incorporates planning of system improvements and schedules, adjustment of procedures, planning of experiments, purchasing equipment and shipping of 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 experiment phase 2019 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. Participants

A summary of the characteristics of the study participants for the CT and WL measurements is listed in Table 3 with corresponding detailed descriptions in subsection 3.2.1 and 3.2.2.

3.3.1. Crew time

During the winter season 2019, 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 operation 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 winter season 2018 as MTF on-site operator.

Table 3
Characteristics of the study participants for the CT and WL measurements.

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

The five members of the OOT 2019, who worked in the MTF during the winter season 2019, 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 summer season 2018/2019, this did not include practical work on plants.

3.3.2. Workload

Four different participant groups operating the MTF were surveyed about their WL. 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 (Bamsey et al., 2014) and the testing phase in Bremen in 2017 (Schubert et al., 2018) as well as in the operation process since 2018 (Schubert et al., 2018; Vrakking et al., 2020b).

The second group included two participants of the five OOT 2019 members mentioned in subsection 3.2.1 who worked in the MTF during the winter season 2019.

The third investigation group included four participants of the nine OOT 2020 members who worked in the MTF during the winter season 2020. Due to the fact that the initial seeding was already done during the summer season 2019/2020 together with the SMT 2019/2020 (see Fig. 2), it was possible, in contrast to the winter season 2019, 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 3.2.1 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 winter season 2018 as the MTF on-site operator.

3.4. Measurements

3.4.1. Crew time

The CT in 2019 was measured during the 209 days of the experiment phase 2019 (see Fig. 2). There were no CT measurements for the winter season 2020.

The RST 2019 tracked their CT for every specific task manually, using a watch or smartphone, and individually for every team member of the RST. The gathered information was documented into 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 experiment phase 2019. There were no tasks related to remote support conducted by the RST after 12.11.2019, nevertheless the MTF was still in operation until the final harvest during the CT experiment phase 2019 (see Fig. 2).

In contrast to the RST 2019, the OOT 2019 manually tracked their CT 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 CT experiment phase (see Fig. 2). The CT 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 CT 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 CT 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 to 20 min each way depending on the weather conditions (Zabel et al., 2019). For some specific tasks CT values were documented in detail.

The time needed to perform the measurement for all CT measurements such as looking on the watch and documenting timespans was not considered. This was done due to the fact that it was only in the range of a few seconds and for that reason considered as insignificant.

3.4.2. Workload

To get an overview about all WL aspects related to operations of a space analogue greenhouse and to find potential possibilities for improvement of the WL, the NASA TLX is used in this work. The NASA TLX is a multi-dimensional rating procedure that comprises six dimensions to assess the WL from one or more operators: mental demand, physical demand, temporal demand, own performance, effort and frustration (NASA ARC 1986; Hart, Staveland 1988).

The 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 for a 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. (Hart 2006)

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 twenty-step bipolar scale, which ranges from a score of 0 to 100 (in increments of 5). To calculate an overall WL 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 WL score with a value ranging from 0 to 100. (NASA ARC 1986; Rubio et al., 2004; Bustamante, Spain 2008)

The SMT 2019/2020 worked 60 days in Antarctica during their summer season (see Fig. 2). They assessed their WL 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 per day 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 experiment phase 2019 (see Fig. 2). They assessed their WL on-site in Antarctica near the end of the summer season 2019/2020 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 per day over this period. During the period in which the greenhouse was full of mature plants this value was approximately 3 CM-h per day.

The four participants of the nine OOT 2020 members worked approximately 2 CM-h per day on MTF related tasks. This group assessed their WL in the first month of the winter season 2020 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 experiment phase 2020 and for the assessment of the WL of the OOT 2020 with respect to activities related to the MTF in the course of the winter season 2020.

The WL of the RST 2019 was assessed on 20.08.2020 (one participant) for their remote support during the experiment phase 2019 (209 days) and the WL of the RST 2020 on 16.09.2020 (one participant) for the remote support during the, at that time still ongoing, experiment phase 2020. Even though the assessment was carried out for two different experiment phases, the average of the results is presented in Section 4.2 since the tasks executed by both groups are similar.

4. Results

4.1. Crew time

4.1.1. Overall assessment

Table 4 shows the CT 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 EDEN ISS experiment phase 2019.

Table 4
CT development over the course of the EDEN ISS experiment phase 2019 on a monthly basis for the OOT 2019 and the RST 2019. Values marked with * are estimated based on single point measurements and on the average value of the measured CT needed for the work in the MTF 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	0.00	0.75	0.00	0.00	1.50	1.50	0.75 [a]	2.25
May	6.00	5.00	11.25	4.25	4.00	26.50	30.50	65.75 [a]	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	137.5
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	0.00	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	67.5
November	0.75	0.00	0.00	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

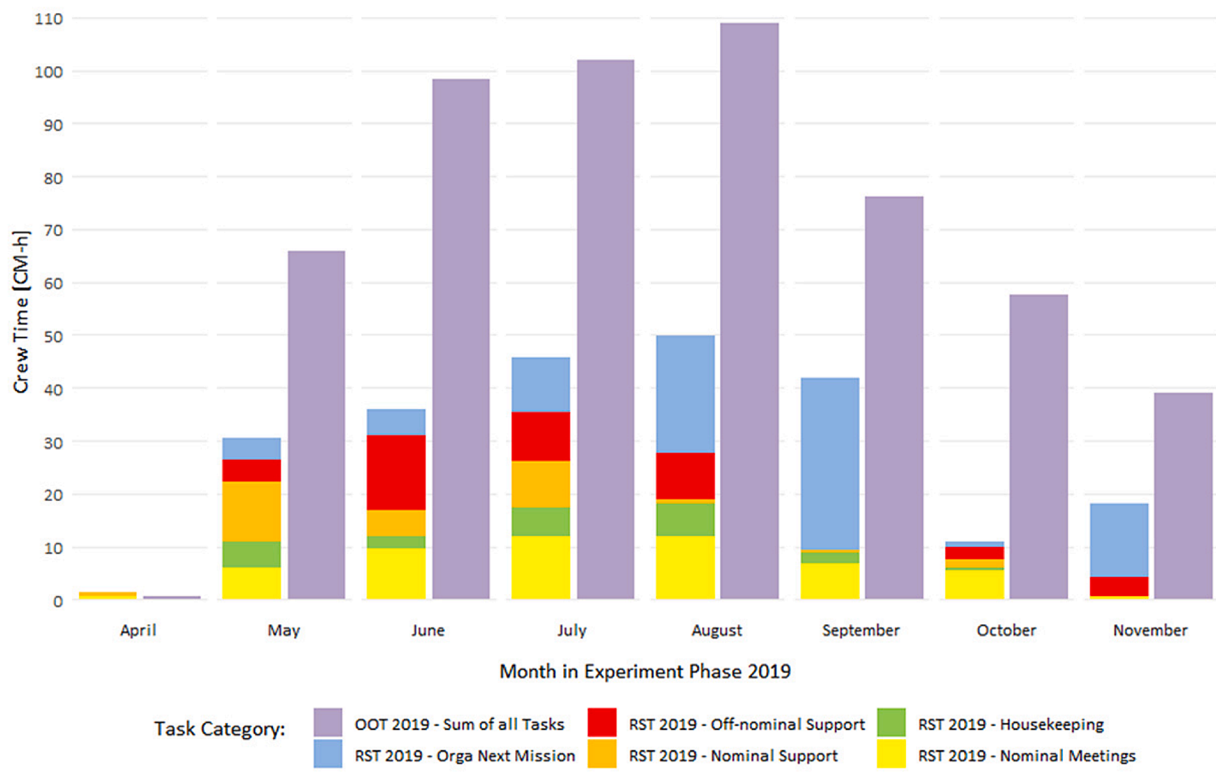

Fig. 3. CT development over the course of the EDEN ISS experiment phase 2019 on a monthly basis for the OOT 2019 and the RST 2019. The OOT CT values for April and May are estimated based on single point measurements and on the average value of the measured CT needed for the work in the MTF between 03.06.2019 and 13.10.2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

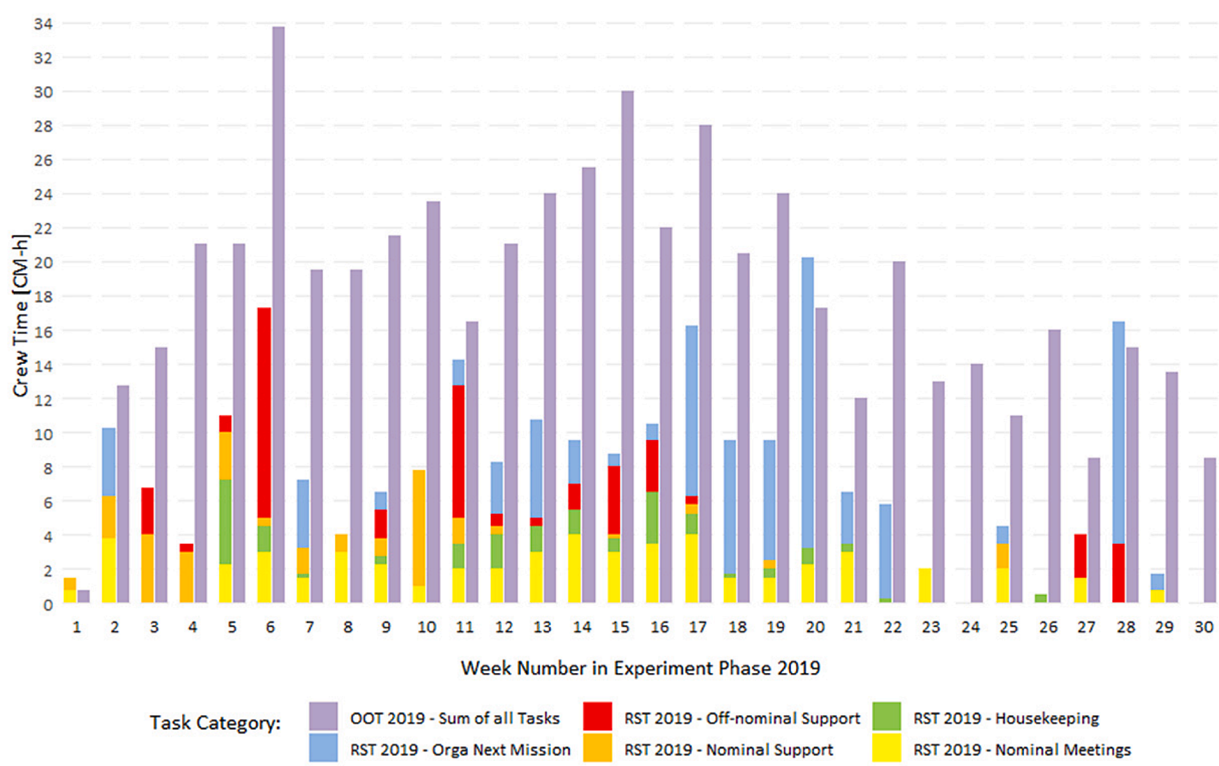

Fig. 4. CT development over the course of the EDEN ISS experiment phase 2019 on a weekly basis for the for the OOT 2019 and the RST 2019. The OOT CT values for April and May are estimated based on single point measurements and on the average value of the measured CT needed for the work in the MTF between 03.06.2019 and 13.10.2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The CT 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 CT of 146 CM-h for the RST 2019, not considering the organizational work for the next mission. Adding the CT of 88.75 CM-h for the organizational work for the next mission, the total CT for the RST 2019 increases to 234.75 CM-h. Dividing these values by the 30 weeks of the experimental phase 2019, the average amount of approximately 4.9 CM-h per week (without the organizational work for the next mission) and 7.8 CM-h per week (including the organizational work for the next mission) can be calculated. By far the highest CT amount occurred related to organizational work for the next mission followed by the CT needed for the nominal meetings. CT dedicated to off-nominal support is on the third rank. The CT needed for housekeeping and nominal support is nearly the same and has the lowest value for the RST 2019.

The total CT for the OOT 2019 adds up to 548.5 CM-h or approximately 18.3 CM-h per week using the 30 weeks of the experimental phase 2019. This amount is almost four times higher than the amount of CT needed for the remote support in 2019, without the CT for the organizational work for the next mission, and more than double the total amount of the remote support CT in 2019, when including the CT 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 CT for the OOT 2019 of approximately 21.3 CM-h can be calculated.

The overall CT needed for operating the EDEN ISS greenhouse during the experimental phase 2019, meaning the sum of the CT 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 per week.

4.1.2. *Monthly and weekly development*

In Fig. 3 and Fig. 4, the development of the CT over the course of the experiment phase 2019 is shown on a monthly, respectively weekly, basis for the OOT 2019 and the RST 2019.

It can be derived from Fig. 3 that the total CT development over the course of the EDEN ISS experiment phase 2019 for the RST 2019 and OOT 2019 on a monthly basis shows a similar trend (see also Table 4). Because the experimental phase 2019 started on 29.04.2019, CT values for April are almost zero. The CT values for the OOT 2019 increase during the first months of operation to a maximum of 109 CM-h per month in August. Nevertheless, it can be seen that the values between June and August are quite similar and range between 98.25 CM-h and 109 CM-h per month (see also Table 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 Fig. 4). Only preparation work for the startup of the system was performed in the beginning of May. Younger plants in the first months resulted in less work. Also, the monthly RST 2019 CT (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 CT, it reached a maximum of 35.5 CM-h per month already in July. This development can also be seen in Fig. 4 with an increase of CT from week 1 to week 15 (beginning of August). Nevertheless, the RST 2019 CT values were in a similar range between week 2 and week 17, when not considering CT for off-nominal events and organizational work for the next mission (see Fig. 3 and Fig. 4).

Only week 6 in Fig. 4 shows a higher CT amount of 33.75 CM-h per week, which is also the maximum value of all weeks of the experiment phase 2019. During that week, the OOT 2019 had to counteract a massive growth of biofilm inside the nutrient solution and in the

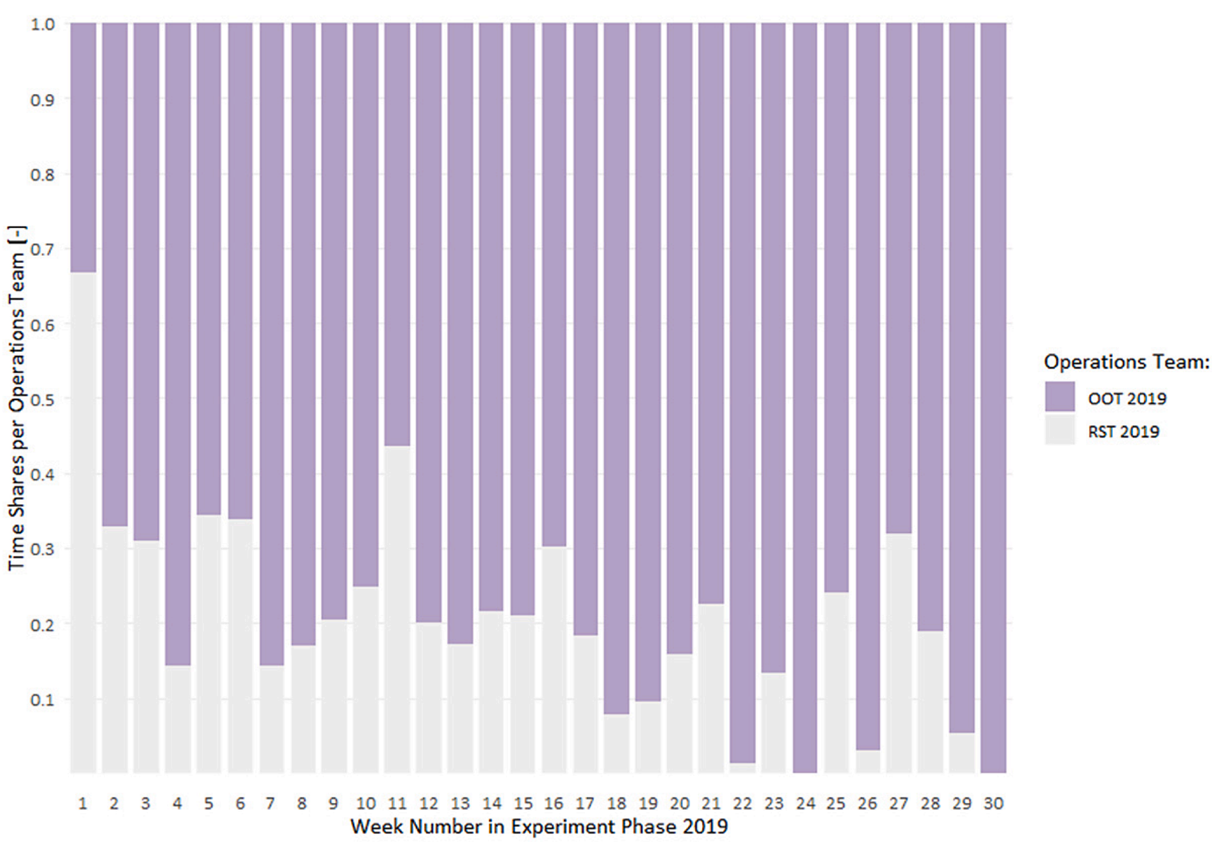

Fig. 5. Development over the course of the EDEN ISS experiment phase 2019 on a weekly basis for the time shares of the total CT for the OOT 2019 and the RST 2019 (without organizational work for the next mission) related to the overall CT. The OOT CT values for April and May are estimated based on single point measurements and on the average value of the measured CT needed for the work in the MTF between 03.06.2019 and 13.10.2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

nutrient lines, which resulted in a lot of work to clean the system. In addition, a failure of the thermal control system (TCS) occurred, which had to be handled as quickly as possible to keep the plants alive. The free cooler valve of the TCS 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, together with support from the RST 2019, solved the issue by fixing the power connector inside of the valve actuator.

Also, in week 11 (see Fig. 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 in 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 EC control sensor causing the nutrient delivery system (NDS) 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 CT can be seen in Fig. 4. It can be seen that the OOT 2019 CT in week 11 is still smaller than the corresponding CT 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 CT and could be solved mostly from remote.

Starting at week 16 (mid of August), the weekly CT of the OOT 2019 decreased (see also September to November in Fig. 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 independencies 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 operation of the MTF (e.g., less things to discuss). In addition, the number of plants was reduced in week 24 (see Fig. 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 CT related to work in the MTF at the end of the experimental phase 2019. All these incidents also affected the RST 2019 CT in a similar way. In August, the RST CT value decreased already to 27.75 CM-h per month with a high reduction of CT in September (9.5 CM-h per month), October (10 CM-h per month) and November (4.25 CM-h per month).

The CT needed for the nominal support category was approximately around 8.3 CM-h per month during the first months (May to July) and decreased to approximately 0.7 CM-h per month for August to November. In addition, the CT for the nominal meeting category increased to a maximum of 12 CM-h per month in July and August and decreased afterwards, also because of the transition from weekly to bi-weekly nominal meetings. The CT needed for the housekeeping category was also higher in the beginning with an average value (May to August) of approximately 4.75 CM-h per month. From September to November, the average value decreased to approximately 0.9 CM-h per month. Considering the organizational work for the next mission, it can be seen that the CT 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.

Fig. 6. Development over the course of the EDEN ISS experiment phase 2019 on a weekly basis for the time shares per RST task category related to the total RST 2019 CT (without organizational work for the next mission). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
NASA TLX adjusted rating of dimensions and overall WL scores including SEM for the corresponding crews on-site in Antarctica and the remote support teams at MCC in Bremen.

	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	0.0	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	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	0.0
Effort	175.0	35.0	152.5	87.5	103.8	25.1	132.5	77.5
Frustration	0.0	0.0	0.0	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**

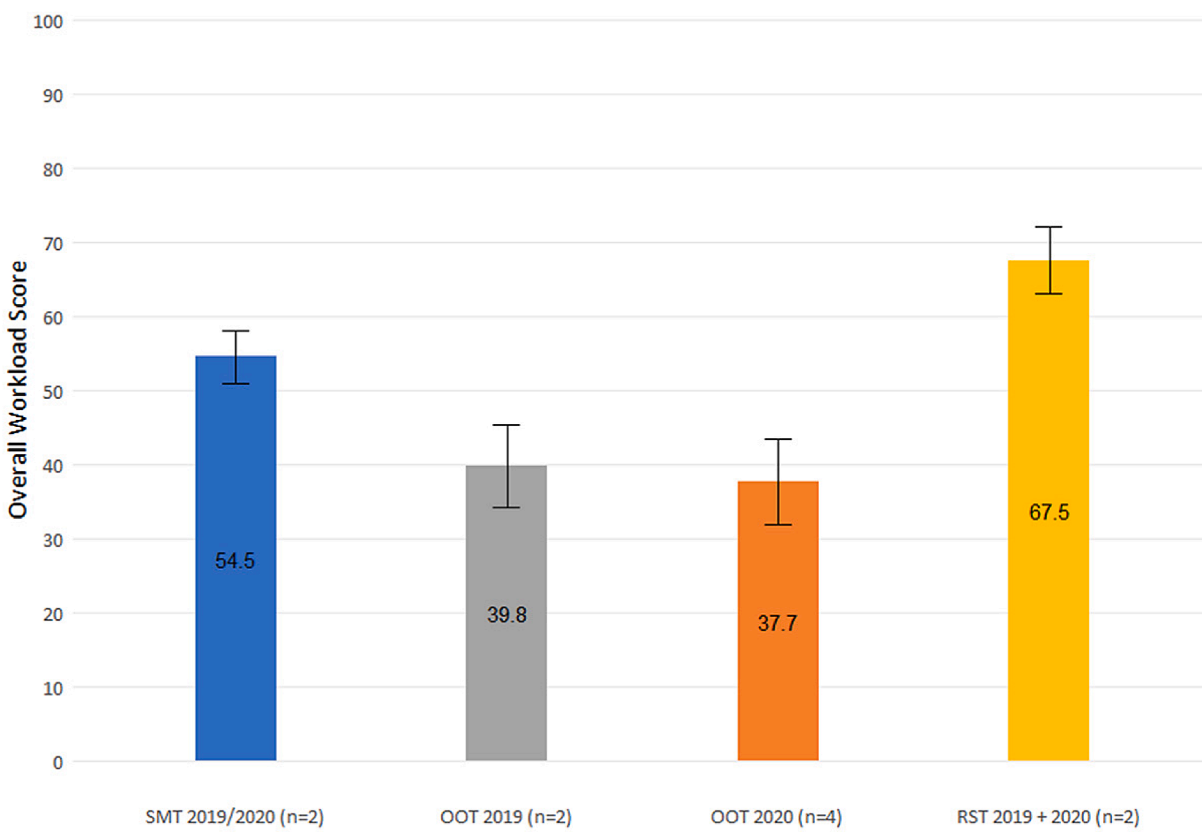

Fig. 7. NASA TLX overall WL scores including SEM for the corresponding crews on-site in Antarctica and the remote support teams at MCC in Bremen.

4.1.3. Analysis of time shares

Fig. 5 shows the development, on a weekly basis, of the time shares of the total CT for the OOT 2019 and the RST 2019 (without organizational work for the next mission) related to the overall CT over the course of the experiment phase 2019. Fig. 5 implies that the time shares of the total CT for the RST 2019 regarding the overall CT were higher in the first half of the experiment phase 2019 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 experiment phase 2019 and a second outlier in week 11 (44%) due to a previously described bigger off-nominal event.

In the second half of the experiment phase 2019 starting at week 16, the time shares of the total CT for the RST 2019 are between 0% and 32% (average of 13%). The values fluctuated based on events in the greenhouse like additional nominal support in week 25 (planning of on-site tasks for the rest of the experiment phase 2019) or off-nominal events in week 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 CT for the RST 2019 (without organizational work for the next mission) during the whole experiment phase 2019 is 21%. The trend derived from Fig. 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 experiment phase 2019. This can also be seen in the reduction by 61% of total CT values of the RST 2019 from 104.75 CM-h (7 CM-h per week) during the first 15 weeks to 41.25 CM-h (2.75 CM-h per week) during the last 15 weeks. For the OOT 2019 the reduction of the total CT values between the first 15 weeks with a value of 305.25 CM-h (20.35 CM-h per week) and the last 15 weeks with a value of 243.25 CM-h (16.22 CM-h per week) is lower, but still significant at roughly 20%.

The development, on a weekly basis, of the time shares for the categorized RST 2019 CT (without organizational work for the next mission) over the course of the experiment phase 2019 is depicted in Fig. 6. Since the off-nominal support activities occurred randomly and are in general not predictable, they are not depicted in Fig. 6 for further investigations.

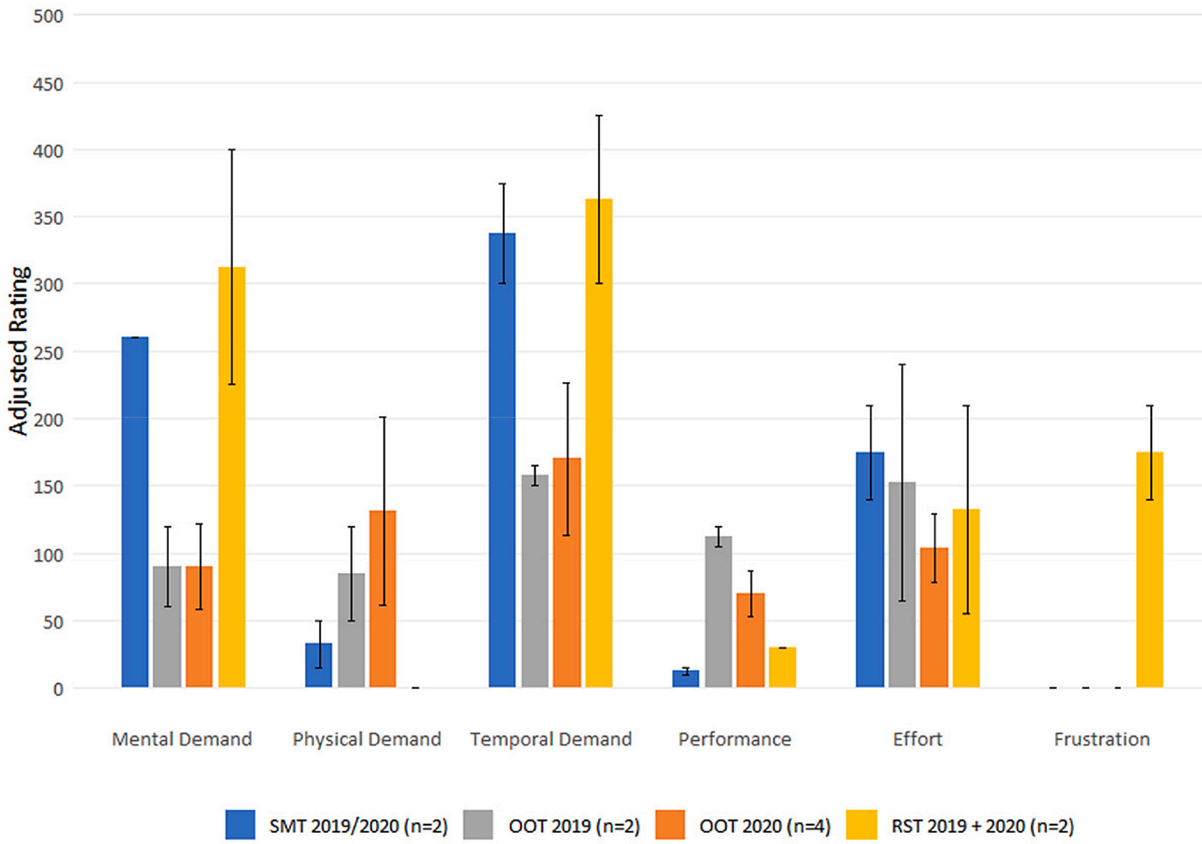

Fig. 8. NASA TLX adjusted rating of dimensions including SEM for the corresponding crews on-site in Antarctica and the remote support teams at MCC in Bremen.

It can be seen that the time shares for the nominal support category related to the total RST 2019 CT 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 experiment phase 2019 with smaller outliers. At the same time the time shares for the nominal meetings continuously increased until the end of the experiment phase 2019. It can also be derived that the time shares for the housekeeping category are relatively constant between week 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 CT required for housekeeping activities was nearly not needed anymore (see also Fig. 4) and just emerged in week 22 and 26 as the only occurrences of this activity for the RST 2019 in these weeks.

Also, the trend depicted in Fig. 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.

4.2. Workload

Table 5 shows the NASA TLX adjusted rating of dimensions and overall WL scores with standard error of the mean (SEM) for the corresponding crews on-site in Antarctica and the RST at the MCC.

4.2.1. Overall workload score

Fig. 7 and Table 5 show the overall WL 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 WL score of all participants of the four groups. The results of the WL 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 WL 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 Fig. 7, while the SEM is a little higher.

4.2.2. Adjusted ratings

In Table 5 and Fig. 8, the adjusted ratings of the six NASA TLX dimensions for the SMT 2019/2020, the OOT 2019 and OOT 2020 as well as the RST 2019 + 2020 are investigated. The values are derived from the averaged adjusted ratings of all participants of the four groups.

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 Fig. 8) compared to the two winter groups with almost similar values. The RST 2019 + 2020 has an even higher value (highest score in Fig. 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 (2 people each 8 h per day) in the short summer season 2019/2020. In contrast, the OOT 2019 worked an average of 2.6 CM-h per day and the OOT 2020 2 CM-h per day. 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 CT of approximately 4.9 CM-h per week (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=0.0) 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 Fig. 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 (Woeckner 2020). 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 grow season starts. The RST 2019 + 2020 had to resolve issues in case of off-nominal events quickly, observe the MTF remotely and had to plan the procedures and schedules executed by the OOT 2019 and OOT 2020 in Antarctica.

The **effort** assessment of the four groups resulted in WL 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 winter season 2020 compared to the winter season 2019. 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 0.0 (SEM=0.0).

The OOTs during the winter seasons sometimes had to walk to the greenhouse several times per day (Woeckner 2020). In addition, nutrient solution exchange including cleaning of 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 (Woeckner 2020), 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). The RST 2019 + 2020 on the other hand did not have to perform any physical work at all.

Considering the **performance** assessment, the SMT 2019/2020 has the second lowest value in Fig. 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=0.0), which is the third lowest value in Fig. 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. (Woeckner 2020) 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 (Schubert et al., 2018). 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 0.0 (SEM=0.0) for all participants of the SMT 2019/2020, the OOT 2019 and OOT 2020, since no participant out of these groups rated frustration over another dimension. In case of the RST 2019 + 2020, frustration is ranked on 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 e.g., failures of the system. In case of the RST 2019 + 2020, this direct feedback of their work was not possible and was not reducing the frustration level.

Overall, the SMT 2019/2020 and the RST 2019 + 2020 have the highest values in Fig. 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 (see Fig. 8). The overall WL 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 ANOVA on the six 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 WL 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.

5. Discussion & conclusion

It is crucial to point out that WL and corresponding CT strongly depend on the system architecture especially with respect to maintenance procedures (Zabel et al., 2019). 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 CT and WL values in this paper can only give implications for the values, which will emerge during future planetary surface missions incorporating a greenhouse. Conversely, CT and WL data on existing architectures can inform the further design and development activities of future greenhouses with the aim to minimize CT and WL. This is also applicable for the CT values gathered at other space analogue test sites on Earth (Eckart 1996) or onboard the ISS (Stromgren et al., 2018).

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 paper for the operation 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 CT 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 paper, despite 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 analogue 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 from the MCC. Nevertheless, the MCC will be involved in case nominal or off-nominal support is required by the astronauts.

The experiment phase 2019 in Antarctica has shown that maintenance and repair activities hold a significant share of the total CT for the OOT needed to operate a planetary surface greenhouse such as already reported by Schwartzkopf (1991) for the BIOS-3 experiments, Russell et al., (2006) for activities onboard the ISS and Zabel et al., (2019) for EDEN ISS experiment phase 2018. Russell et al., (2006) reported that the CT of three astronauts on ISS for habitat maintenance accounted to 1.9 CM-h per crew member per day and 2.4 CM-h per crew member per day 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 (Stromgren et al., 2018).

This implies that one way to minimize the CT needed for the operations of future planetary surface greenhouses is to implement a higher degree of automation into the greenhouse regarding maintenance activities (Eckart 1996; Kang et al., 2000). But higher automation with respect to plant cultivation tasks such as harvesting or transplanting would also be beneficial (Schwartzkopf 1991). This would reduce the CT and WL needed for executing the automatized activity, while increasing the CT for maintenance tasks due to a more complex system architecture (Schwartzkopf 1991). Hence, a tradeoff analysis prior to the installation of a more automated system has to be done to determine if CT could be reduced by implementing the automated system. But not all activities related to plant growth should be automated to keep the positive effect of the plant interaction on the psychological wellbeing of the astronauts (Poulet et al., 2014).

Another way to minimize CT and WL 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 astronauts working more efficiently in earlier stages of their missions. As a result CT and WL 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 WL is coupled to CT and vice versa. This can be explained by the fact that one dimension of the TLX is temporal demand. However, no direct relation can be drawn between WL and CT. Although, the CT of the OOT 2019 is almost four times higher compared to the CT of the RST 2019 (without organizational work for the next

Table 6
Fresh edible biomass output and corresponding production values for different experiments. Values marked with * as reported by (Zabel et al., 2020), values marked with $^{+}$ as reported in (Patterson 2011) and values marked with $^{\circ}$ as reported in (Patterson et al., 2012).

<table>
<tr><th>Experiment</th><th>Fresh Edible Biomass [kg]</th><th>Growth Area [m²]</th><th>Duration of Experiment [days]</th><th>Production Rate</th><th>CT On-site [CM-h]</th><th>Adjusted Production Rate</th><th>Edible Biomass per Unit Labor</th></tr>
<tr><td>EDEN ISS experiment phase 2018</td><td>* 268</td><td>* 12.5</td><td>* 286</td><td>* 0.075 kg/(m²*d)</td><td>858 (21 per week)</td><td>0.025 kg/(m²*CM-h)</td><td>0.31 kg/CM-h (3.2 CM-h/kg)</td></tr>
<tr><td>EDEN ISS experiment phase 2019 – OOT 2019</td><td rowspan="3">110</td><td rowspan="3">12.5</td><td rowspan="3">209</td><td rowspan="3">0.042 kg/(m²*d)</td><td>548.5 (18.3 per week)</td><td>0.016 kg/(m²*CM-h)</td><td>0.2 kg/CM-h (5 CM-h/kg)</td></tr>
<tr><td>EDEN ISS experiment phase 2019 – RST 2019</td><td>146 (4.9 per week)</td><td>0.06 kg/(m²*CM-h)</td><td>0.75 kg/CM-h (1.33 CM-h/kg)</td></tr>
<tr><td>EDEN ISS experiment phase 2019 – Grand total</td><td>694.5 (23.2 per week)</td><td>12.67 g/(m²*CM-h)</td><td>0.16 kg/CM-h (6.31 CM-h/kg)</td></tr>
<tr><td>SPFGC</td><td>-</td><td>+ 22.77</td><td>-</td><td>° 0.130 kg/(m²*d)</td><td>+ 23 per week</td><td>-</td><td>+ 0.8 kg/CM-h</td></tr>
</table>

mission), the RST 2019 had perceived higher WL. On the other hand, it is also characteristic that a high CT could as well lead to high perceived WL. This indicates that CT is not the only factor affecting the WL and that WL could be perceived low also in case of high CT demand. Further investigations, and in particular task-specific CT and WL assessments, would be needed to draw significant conclusions on the relationship between CT and WL.

5.1. Crew time

As mentioned previously, for winter season 2019, CT was measured for every specific task individually by every team member of the RST 2019. To minimize the valuable CT of the OOT 2019 designated for the work in the MTF, only the CT 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 CT 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 as well as on the average value of the measured CT needed for the work in the MTF between the start of week 6 and the end of week 24 of the experiment phase 2019. 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 end of week 24 of the experiment phase 2019 depicts the work in the MTF when it was at full plant cultivation capacity.

Due to the fact that the CT 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 CT needed for a specific category as was done for the on-site operator CT of winter season 2018 (Zabel et al., 2019), since the tasks in the EDEN ISS MTF strongly vary during one workday (see Table 7 and Table 8 in the supplementary material for typical workdays of the RST 2019 and the OOT 2019). Nevertheless, it is possible to categorize the CT of the RST 2019.

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

5.1.1. Crew time and edible biomass production comparison

During the 286 days of the experiment phase 2018, 268 kg of fresh edible biomass was produced on 12.5 m^2 growth area in the MTF. This results in a production rate for the experiment phase 2018 of 0.075 kg/(m^2*d). (Zabel et al., 2020) In contrast, 110 kg of fresh edible biomass was grown during the experiment phase 2019. 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/(m^2*d), which is almost half of the experiment phase 2018 value.

This deviation in biomass output per area between the experiment phases 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 experiment phase 2019 was 77 days shorter compared to the experiment phase 2018 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 experiment phase 2018. Thus, also, the biomass output per area could be lower.

Moreover, there was an additional wintering crew member at NM III dedicated for the operation of the greenhouse during the experiment phase 2018. This on-site operator from DLR worked 3 CM-h per day (858 CM-h during the whole experiment phase 2018) in the greenhouse. In this CT 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 experiment phase 2018. If this value is considered in the production rate, an adjusted value of 0.025 kg/(m^2*CM-h) corresponding to 0.31 kg/CM-h (3.2 CM-h/kg) edible biomass per unit labor can be calculated.

During the experiment phase 2019 on the other hand, there was no additional wintering crew member dedicated for the tasks in the greenhouse and the OOT 2019, who was not familiar 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 as well as arrangement and the number of plants was drastically reduced at the end of the experiment phase 2019 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 per week on average (548.5 CM-h during the whole experiment phase 2019) in the greenhouse. Considering this for the production rate, an adjusted value of 0.016 kg/(m^2*CM-h) corresponding to 0.2 kg/CM-h (5 CM-h/kg) edible biomass per unit labor can be calculated. This value is still smaller compared to the one of the experiment phase 2018. But in contrast to the experiment phase 2018, the CT values of the experiment phase 2019 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 CT of 146 CM-h during the whole experiment phase 2019 (without organizational work for the next mission) can be calculated to 0.06 kg/(m^2*CM-h) corresponding to 0.75 kg/CM-h (1.33 CM-h/kg) edible biomass per unit labor. The value for the sum of the total CT of RST 2019 and OOT 2019 of 694.5 CM-h during the whole experiment phase 2019 (without organizational work for the next mission) can be calculated to 12.67 g/(m^2*CM-h) corresponding to 0.16 kg/CM-h (6.31 CM-h/kg) edible biomass per unit labor.

The SPFGC had a production rate of 0.130 kg/(m^2*d) (Patterson et al., 2012). This rate is higher compared to the values of the MTF during the experiment phases 2018 and 2019. The SPFGC operator worked 23 CM-h per week in the greenhouse with a growth area of 22.77 m^2 inside the Amundsen-Scott South Pole station (Patterson 2011). Patterson (2011) reported a 0.8 kg/CM-h edible biomass per unit labor. The corresponding value with 0.2 kg/CM-h for the EDEN ISS experiment phase 2019 is four times smaller.

The difference between the values from the SPFGC and the EDEN ISS experiment phase 2019 can be explained by similar reasons mentioned previously for the comparison with the EDEN ISS experiment phase 2018. Also in the SPFGC a dedicated on-site operator was responsible for the activities related to the greenhouse (Patterson et al., 2012). Moreover, CT required for repairs and maintenance activities for primary hardware systems as well as CT of volunteers was not considered for the operations of the SPFGC (Patterson 2011). Due to the fact that the SPFGC was incorporated inside the Amundsen-Scott South Pole station (Patterson et al., 2012), no CT was needed for walking back and forth to the greenhouse. For the EDEN ISS experiment phase 2019, all these activities were incorporated in the measurements, resulting in a comparatively lower kg/CM-h value. In addition, the SPFGC produced a high amount of cucumbers (41% of the total fresh edible biomass) (Zabel et al., 2020) compared to the 14.5% produced during the EDEN ISS experiment phase 2019. As reported in Zabel et al., (2020), cucumbers had the highest production rate per unit area and time of the plants grown in the MTF in the experiment phase 2018. 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 CT caused by remote support were found in the literature.

The OOT 2019 worked 12.60 CM-min/(m^2*d) inside the MTF. Although there are considerable differences in facility design, this value is higher than the values found in literature for the previously mentioned MDRS mission with a value of 9 CM-min/(m^2*d) (Poulet and Doule 2014) or the BIOS-3 experiment from December 1972 to June 1973 with a value of 8 CM-min/(m^2*d) (Schwartzkopf 1991; Eckart 1996). Only the measurements taken during a HI-SEAS mission in 2014 show a higher value of 31.2 CM-min/(m^2*d) (Poulet et al., 2014).

5.1.2. Crew time development over time

The analysis of the CT in this paper has shown that there is a shift of CT over time. The CT 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 CT 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 the fact that the number of plants was reduced at the end of the experiment phase 2019. The CT development of the OOT 2019 showed a similar behavior.

The increasing independence of the OOT 2019 from the RST 2019 over the course of the experiment phase 2019 can also be seen in the fact that the time shares for the nominal support category related to the total RST 2019 CT (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 CT for the RST 2019 (without organizational work for the next mission) related to the overall CT decreased over the course of the experiment phase 2019 with fluctuations caused by off-nominal events and additional nominal support. Accordingly, the time shares of the total CT increased for the OOT 2019.

5.1.3. Remote support crew time categorization

Stromgren et al., (2018) proposed a methodology for CT categorization, which could be used for future CT investigation to allow for a comparison between studies. One important aspect to mention is that the categorization of Stromgren et al., (2018) did not incorporate CT values for planetary surface greenhouse tasks at all, since the values were based on tasks onboard the ISS.

In this paper, a first categorization methodology for CT 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 CT measured in planetary surface greenhouse studies as a baseline for the planning/design process for future space missions, in which CT requirements should be considered as early as possible (Russell et al., 2006). This will help to understand which tasks are required and based on that, to better assess the amount of CT needed for such missions in order to decrease the deviations of planned CT from actual CT discovered in Russell et al., (2006).

It has been suggested by the authors of this paper that 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 CT for remote support would be inflated by the CT for science related activities, which are not necessarily utilized to operate the greenhouse for the purpose of e.g., food production, air or water recycling. Using science inflated CT values could result in the decision against greenhouses during the planning of future space missions on account of too high CT numbers, 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 CT 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 CT demands to the corresponding category subsequent to the meeting.

5.1.4. Potential enhancements of future measurements

The collected measurements may incorporate inaccuracies to some extent. The time period of the experiment phase 2019 was quite long and the RST 2019 as well as the OOT 2019 had to record their CT every day. Due to this, the performance of the CT recordings may have decreased over the course of the experiment phase 2019. In addition, participants may have forgotten to record their CT immediately after performing the tasks and recorded it at a later point in time based on their memory, which might have influenced the measurements.

To increase the accuracy of the CT 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 CT of the greenhouse operators (RST and OOT).

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

In addition, investigations of CT with respect to the crop nutrient content would contribute to field of research in a significant way, as the nutritive aspect of plants will be key in future long-duration space mission scenarios (Douglas et al., 2016). 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 time such as lettuces, herbs or cucumbers, like investigated in the EDEN ISS project (Dueck et al., 2016), as supplemental diet to the pre-packed MREs (Schubert 2017). 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), CT and edible biomass quantity and quality should be investigated further to aid in crop selection, system design and mission planning.

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 WL between the four evaluation groups for a typical workday in the MTF and during remote operations in the MCC.

The number of participants for the WL evaluation is rather small, but originates from the fact that the number of people operating the greenhouse per year is small.

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

5.2.1. Comparison of workload values

The WL investigations for all groups involved in the operation of the MTF during the winter season 2019 to 2020 have indicated that the RST 2019 + 2020 perceived the highest WL 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 respectively 37.7.

With the results from Grier (2015), it is possible to grade if an overall WL score of the TLX should be considered high or low in comparison to other TLX studies presented in literature. For this purpose, Grier (2015) studied over 1000 overall NASA TLX WL scores, ranging from 6.2 to 88.5, based on over 200 publications. Grier (2015) did not consider the performance of the participant. If a WL is perceived as acceptable not only depends on the WL value itself but also depends on the contextual variables such as level of expertise, situation or task type (Grier 2015; Braarud 2020).

Compared to the overall WL score values presented in Grier (2015), 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 deciles is 68.0. A direct comparison with WL scores for planetary surface greenhouse, other analogue 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 have influenced the assessment of the WL. 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 wellbeing, 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 WL of the operation teams (RST and OOT) as much as possible.

5.2.2. Different preconditions of the on-site operator teams in 2019 and 2020

In contrast to the OOT 2019, which started their work in the greenhouse after a couple of months of the greenhouse hibernation phase, the OOT 2020 started their 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 winter season 2020 with hands-on experience on the plants or system handling during the summer season 2019/2020, which was not possible for the OOT 2019. Nevertheless, no differences in overall WL 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 experiment phases 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 summer season 2019/2020, compared to the OOT 2019 resulting in similar perceived overall WL. Another impact on the overall WL could be the possibility that the differences in the amount of time spent for the basic system training was not enough to make a difference in perceived overall WL of the OOT 2019 and the OOT 2020. One factor to add is that the overall WL of the OOT 2019 was measured at the end of the experiment phase 2019. On the other hand, the experiment phase 2020 was still running, when the WL of the OOT 2020 was measured. Another assumption is that the perceived WL maybe would have changed over the course of the full experiment phase 2020, 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 WL assessment, if done at the end of the full experiment phase 2020. Although the OOT 2019 maintained work reports during the experiment phase 2019 to track the work that they carried out in the greenhouse, these did not include WL assessments and as such the WL evaluation was based purely on memories and feelings at the time of the evaluation. This could also alter the results of the overall WL measurement.

5.2.3. Potential enhancements of future measurements

The collected measurements may incorporate inaccuracies to some extent. The fact that the SMT 2019/2020 already had experienced a couple of summer seasons in Antarctica could have an impact on the evaluation compared to the OOT 2019 and OOT 2020. The SMT 2019/2020 could have a bias based on the previous experienced summer seasons, rating the experienced WL in summer season 2019/2020 higher (or lower) by comparison. The same applies for 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 wintering crew 2018. The OOT 2019 and OOT 2020 on the other hand do not have any reference operating a space analogue planetary surface greenhouse, which might influence their evaluations as well.

Also, in case of WL measurements, further investigations regarding the perceived WL 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 WL measurements for specific tasks over a longer period, it would be possible to also perform statistical investigations.

It is planned to conduct WL 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 WL measurements will be conducted repeatedly right after task execution to investigate which procedures are more WL intense than others. Moreover, additional CT measurements are planned to gain more insight in the link between CT and WL.

Declaration of Competing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.lssr.2021.06.003.

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