49th International Conference on Environmental Systems
7-11 July 2019, Boston, Massachusetts ICES-2019-138

Crewtime in a Space Greenhouse based on the Operation of the EDEN ISS Greenhouse in Antarctica

Paul Zabel*, Conrad Zeidler*, Vincent Vrakking*, Markus Dorn* and Daniel Schubert*
German Aerospace Center (DLR), 28359 Bremen, Germany

The EDEN ISS project partners deployed a space greenhouse analogue at the Neumayer Station III in Antarctica in January 2018. The greenhouse is incorporated in two interconnected 20 foot shipping containers and positioned around 400 meters away from the research station. All subsystems required for plant cultivation are inside this so called Mobile Test Facility. The cultivation area of around 12.5 m² is arranged in a shelf-like structure in one of the containers, while the other container houses the subsystems and a small working area. Between February and November 2018 one of the authors was the only on-site operator of the greenhouse. In that time it was his responsibility to cultivate various plants and to execute numerous experiments. One of the experiments was the determination of the crewtime required for plant cultivation. A formula to calculate the crewtime use inside a space greenhouse has been developed. This paper also presents crewtime values for various activities related to the operation of a space greenhouse. The focus is on the tasks related to plant cultivation such as sowing, pruning, harvesting and cleaning. Crewtime has been measured independently for different crop species, because each crop species requires different tasks to be performed during cultivation. Additionally, the task schedule and related crewtime of complete workdays have been documented at several occasions during the nine months of operation of the EDEN ISS greenhouse in Antarctica.

Nomenclature

AMS	=	Atmosphere Management Subsystem
BVAD	=	Baseline Values and Assumptions Document
CT	=	Crewtime
ECLSS	=	Environmental Control and Life Support Systems
FEG	=	Future Exploration Greenhouse
GH	=	Greenhouse
ISPR	=	International Standard Payload Rack
MTF	=	Mobile Test Facility
NDS	=	Nutrient Delivery Subsystem
NM III	=	Neumayer Station III
N.A.	=	Not applicable
N.M.	=	Not measured

I. Introduction

The EDEN ISS Mobile Test Facility (MTF) was successfully deployed in Antarctica in January 2018 after three years of design, development and construction. The MTF houses the Future Exploration Greenhouse (FEG), which is a space greenhouse test facility with a cultivation area of 12.5 m² and a Service Section which contains the subsystem necessary to run the FEG and a work desk including a sink. A detailed description of the design process of the MTF and its components, plant selection and project development can be found elsewhere [1–8].

The MTF is located 400 meters south of the German Neumayer Station III (70°40´S, 008°16´W) on the Ekström ice shelf in the vicinity of the Atka Bay. The station is operated year-round with a summer (November to February) crew of 50-60 people and a winter (February to November) crew of 9 people. During the winter period are no supply missions able to reach the station, which means that all supplies (e.g. food, spare parts, tools) need to be delivered during the few summer months. This remoteness makes the Neumayer Station III (NM III) an excellent test area for human space exploration test missions.

* Research Associate, Institute of Space Systems, Robert-Hooke-Str. 7, 28359 Bremen, Germany.

In 2018 a tenth person complemented the wintering crew to operate the MTF. The operation started in February 2018 and was continued throughout the whole winter-over season 2018. The first plants were sown on February 7 and subsequently transferred to the cultivation trays in the following weeks. The plants developed very well and the first harvest occurred on the March 20. This harvest included lettuces, radishes, Swiss chard and other leafy greens. The first harvest of cucumber (March 29) and tomatoes (May 16) followed soon after. The last harvest of the 2018 winter season was executed on November 20. Until then a total edible fresh biomass of 67 kg cucumbers, 46 kg tomatoes, 19 kg of Kohlrabi (a type of cabbage), 8 kg of radish, 15 kg herbs, 56 kg of lettuce, 51 kg of leafy greens and 1.5 kg of sweet pepper was harvested from the plants grown inside the FEG. Most of the produce was consumed by the wintering crew except for a small portion that was set aside for measurements and sampling.

Furthermore, a large number of experiments and measurements have been conducted by the on-site operator (Paul Zabel) which included research in the fields of food quality and safety, microbial environment, horticulture, greenhouse subsystem validation, plant health monitoring, impact of the greenhouse on the crew, electrical energy demand, remote operation and crewtime demand. The results of the latter are described in detail in this paper.

II. Crewtime in Space Missions

Crewtime is a precious and limited resource in every human spaceflight mission. The cost of crewtime is correlated with the cost of life support system cost (i.e. system mass and consumables) necessary to sustain the crew member. While the life support system is required to keep the crew member alive continuously (24 hours per day every day) the work time per day is usually restricted to a maximum of 8 to 8.5 hours per work day with five work days and two rest days per week. The remaining time of the day is reserved for sleep and personal maintenance [9–11]. Only within these 8 to 8.5 hours crew member perform scheduled maintenance and scientific work.

The work in a future space greenhouse could be associated to both, being maintenance work in terms of life support system maintenance, but also scientific in terms of plant cultivation experiments. It is obvious that the crewtime required for the greenhouse maintenance needs to be as small as possible. The science crewtime for experiments inside the greenhouse on the other hand is in competition with other science tasks planned for the mission.

III. Greenhouse Tasks

Tasks within a space greenhouse are of various natures. There are tasks involving the plants, tasks involving the subsystems required to grow the plants, scientific tasks and tasks the need to be done upon subsystem or component failures. Two different categorizations of greenhouse tasks can be found in the literature.

NASA's BVAD document[9] assigns crewtime to tasks related to the components: crops, shoot zone, root zone and water and nutrients, lamps, ballasts, mechanization systems and secondary structure. While this definition seems useful for listing mass, volume, power, thermal control and logistics demands of the different components, it is not accurate for describing crewtime demands within a space greenhouse.

A labor expenditure study performed during the experiments carried out in the BIOS 3 facility[12] separates greenhouse tasks into the four categories: sowing and harvesting plants and wheat trashing, monitoring pf plants' conditions and equipment maintenance, preparation of correcting solutions and sanitary scrubbing of phytotrons. This definition is more detailed than the one in the BVAD, but it mixes individual tasks such as the preparation of the correcting solution with groups of tasks such as equipment maintenance.

A more general categorization of greenhouse tasks is required in order to better understand and visualize the crewtime requirements for different actions. The authors of this paper established the greenhouse task clusters shown in Table 1 in order to analyze the crewtime measurements of the EDEN ISS project, but also as a general set of definitions for future space greenhouse concepts.

The cluster Crop Cultivation encompasses all tasks directly related to crop cultivation. Usually these kinds of tasks also involve the crops themselves, but no other subsystems. Examples for this cluster are typical actions in a greenhouse like sowing, thinning, pruning, harvesting and pollination (when necessary) of crops. Other tasks are plant health monitoring, assessing food quality and safety of the produce and the separation of edible and inedible biomass. Depending on the greenhouse architecture the transfer of plants between different location might also be necessary, e.g. from a nursery to the final cultivation location.

The Maintenance cluster includes all schedulable tasks or recurring actions that are necessary to maintain the functionality of the greenhouse. These tasks normally involve different subsystems and components. The exchange/cleaning of filters, the cleaning of the cultivation area, checking subsystem telemetry, nutrient solution preparation/adjustment, calibration of sensors, filling/emptying/cleaning of tanks, the supply of consumables and waste management actions fall in this cluster.

The main difference of the Repair cluster to the Maintenance cluster is that tasks assigned to the former are sudden and unexpected events that cannot be scheduled and are normally to be avoided. This can be done by putting an emphasis on subsystem and component reliability. However, even the most resilient subsystem or component still as probability of failure. Tasks in the Repair cluster are there to deal with these failures and consequently involve actions like the exchange of broken equipment with spare parts, the repair of broken equipment, the manufacturing of spare parts (in the absence of such), contingency actions to prevent permanent damage to equipment, plants and crew and cleaning actions (e.g. in case of a spill).

The Science cluster incorporates tasks related to scientific experiments, measurements and sampling inside the greenhouse. These kinds of tasks are usually not required for the nominal operation of the greenhouse. However, especially in early space greenhouse there will be most likely a number of scientific activities to improve plant cultivation, subsystems, etc.

Table 1: Definition of greenhouse task clusters.

Task cluster	**Crop Cultivation**	**Maintenance**	**Repair**	**Science**
Definition	Tasks directly related to crop cultivation. Usually involves crops themselves.	Tasks that can be scheduled or a recurring on certain intervals. Usually involves subsystems/components.	Tasks that happen sudden and unexpected and cannot be scheduled. Usually involves subsystems/components.	Tasks that involve scientific measurements or experiments. Usually not mandatory to run the greenhouse.
Typical tasks	Sowing Thinning Pruning Harvesting Pollination Transfer to different location Plant health monitoring Food quality and safety Separation of edible and inedible biomass	Regular exchange/cleaning of components (e.g. filter) Cleaning of cultivation area Check of subsystem telemetry Nutrient solution preparation/adjustment Calibration of sensors Filling, emptying cleaning of tanks Supply of consumables Waste management	Exchange of broken equipment with spare part Repair of broken equipment Manufacturing of spare parts Contingency actions Spill cleaning System/subsystem/ component shutdown	Experiments with crops under different environmental conditions Sampling tasks

IV. Crewtime Formula for Space Greenhouses

A space greenhouse is considered as part of the Environmental Control and Life Support System (ECLSS). Consequently, the crewtime associated with a space greenhouse (CT_{GH}) is one part of the ECLSS crewtime budget (CT_{ECLSS}), as shown in formula (2) where *i* represents other ECLSS subsystems.

$$CT_{ECLSS} = CT_i + \cdots + CT_{GH} \qquad (2)$$

CT_{GH} is the sum of the crewtime demand of the four clusters Crop Cultivation ($CT_{GH\_crop\_cultivation}$), Maintenance ($CT_{GH\_maintenance}$), Repair (CT_{GH_repair}) and Science ($CT_{GH\_science}$):

$$CT_{GH} = CT_{GH\_crop\_cultivation} + CT_{GH\_maintenance} + CT_{GH\_repair} + CT_{GH\_science} \qquad (3)$$

$CT_{GH\_crop\_cultivation}$, $CT_{GH\_maintenance}$, CT_{GH_repair} and $CT_{GH\_science}$ are the sums of the crewtime spend on the respective tasks, as defined in the previous chapter.

V. EDEN ISS Crewtime Measurements

A. Method and materials

Crewtime measurements were performed with a watch or a smartphone. Notes were taken on paper and later filled into an Excel file. No special equipment was used for the measurements. The time required to perform measurements (looking on the watch and noting down timespans) of single task crewtime is only in the range of a few seconds and is assumed negligible. Experiment time for noting down the four workday data sets was in the range of a few minutes. This time is not explicitly mentioned in the datasets. For normalizing the crewtime data a nominal operation period from February 7th (first sowing) to November 20th (last harvest) 2018, which are 286 days, is assumed.

It should be noted, that the crewtime measurements could not be done on every single day throughout the wintering season. The workload for the on-site operator was higher than anticipated and crewtime measurements could only be done when there was enough time to perform this activity. Complete workday datasets were only collected four times throughout the 2018 season. The crewtime data per greenhouse task was collected on several different days during the season. The amount of measurement points is given for each task.

B. A typical greenhouse workday

The on-site operator of the MTF performed a large number of tasks each day most of them will also be required in a future space greenhouse. Usually, the operator spend the morning in the laboratory inside the Neumayer Station III to do office and laboratory work. These tasks include among others checking the system telemetry, communicating with project scientists and engineers, preparation of supplies for the MTF. After lunch the operator went to the greenhouse to work with the plants (e.g. sowing, harvesting), to perform maintenance tasks and experiments. Table 6 and Table 7 in the Appendix of this paper show four typical workdays in the 2018 wintering season. The tables give a good overview about how a workday in a space greenhouse might look like.

There are, however, also Antarctic specific tasks (e.g. shoveling snow, changing cloths) in the tables. The MTF is positioned on a raised platform where the entrance is sometimes covered with snow from a previous storm. This snow needs to be removed in order to enter the greenhouse. Furthermore, the EDEN ISS greenhouse is not located inside the Neumayer Station III, which was not possible, but 400 meters south of the station. The operator needed to equip himself with polar clothing, shoes, etc. to withstand the Antarctic climate before walking the path between the greenhouse and the station. As can be seen in Table 6 and Table 7 this cloth changing and walking required 20-40 minutes one way. The timespan varies a lot with the outside climate which affects the amount of cloths needed and the walking time. The latter can be between 5 minutes during good weather conditions and 20 minutes during stormy conditions. This fact resulted in the decision of the on-site operator to only go once a day to the greenhouse, normally in the afternoon, because there was more time between the appointed meal times. It also required a lot of foresight and planning of the operator to avoid unnecessary trips between the station and the greenhouse.

C. Crewtime per greenhouse tasks

1. Crop Cultivation

Crewtime for crop cultivation tasks is given per crop species and per tray. A tray in this case is the unit in which the plants were cultivated inside the FEG. In the 2018 season configuration, the FEG could house 42 trays of which 4 were dedicated to a plant nursery and the remaining 38 trays used for crop cultivation. One tray is 600 mm long and 400 mm wide. The cultivation area associated to one tray is larger than the tray itself (0.24 m^2) and is around 0.328 m^2, because the plants also use the space around the trays. The total cultivation area of the FEG was around 12.5 m^2 during this season.

Table 2 shows the crewtime per tray for different crop cultivation tasks and different crops measured during the 2018 season. The FEG configuration of 2018 incorporated a plant nursery, which was used to germinated the seeds and house the seedlings for the first 10-30 days depending on the crop species. *Sowing* refers to putting the seeds into the rock wool cubes and the rock wool cubes into the nursery. *Transferring* refers to moving the plants from the nursery to the cultivation tray. Both tasks are only performed ones during the cultivation cycle. *Pruning/Thinning* refers to plant management tasks required for certain crops. Radish plants were initially sown with two seeds per rock wool block, but then required the thinning of seedlings down to one plant per block after germination. Crops which grow indeterminately such as tomato and cucumber plants require pruning from time to time during the cultivation. Pruning in this case means the removal of excess side shoots and flowers and withered leaves. *Harvesting* refers to the removal of edible biomass or inedible biomass from the plant. The former was performed once (e.g. lettuce, radish) or several times (e.g. tomato, cucumber, leafy greens, herbs) during the cultivation period. The latter refers to the removal of the plants at the end of the cultivation cycle.

Although Table 2 lacks data points for sowing and transferring of plants, these two tasks seldom required more than 5 minutes per tray independent of the crop species, the exceptions being chives, parsley and arugula. These crops were not cultivated in rock wool blocks but rather sown on mats of cotton/wool fibers to achieve large plant densities of more than 100 plants per tray. Consequently, the sowing required more crewtime.

Table 2: Crewtime per tray for crop cultivation tasks for different crops. (Shortest and longest crewtime, mean crewtime for N>1 and N are given for each crop and task. Grey marked tasks are not applicable (N.A.) for certain crops. Other tasks were not measured (N.M.) during the 2018 season.)

Crop	**Plants per tray**	**Crewtime per tray per task [min:s]**				
		Sowing	*Transferring*	*Pruning/ Thinning*	*Harvesting edible biomass*	*Harvesting inedible biomass*
Lettuce	6	01:15-02:00 Mean=01:35 N=12	01:15 N=1	N.A.	01:18 N=1	02:54 N=1
Swiss Chard	12	*02:00*[*]	*01:30**	N.A.	04:00-15:00 Mean=07:15 N=8	05:30 N=1
Red Mustard - Red Giant	20	*02:00**	*01:30**	N.A.	04:40-08:00 Mean=06:12 N=9	*04:00**
Red Mustard - Frizzy Lizzy	20	*02:00**	*01:30**	N.A.	03:40-11:40 Mean=06:56 N=9	*04:00**
Mizuna	24	*02:00**	*01:30**	N.A.	08:00-16:00 Mean=11:24 N=4	*04:00**
Arugola	~200	*10:00**	N.A.	N.A.	04:00-13:00 Mean=07:01 N=6	11:15-17:00 Mean=14:25 N=5
Parsley	N.M.	*10:00**	N.A.	N.A.	09:00-34:00 Mean=08:24 N=13	*10:00**
Chives	N.M.	*10:00**	N.A.	N.A.	04:00-09:00 Mean=03:06 N=14	*10:00**
Basil - Dolly	20	*02:00**	03:30 N=1	N.A.	02:00-19:30 Mean=09:31 N=11	06:30 N=1
Radish - Raxe	36	04:00-07:00 Mean=05:00 N=3	N.A.	01:15-02:00 Mean=01:33 N=4	05:00-09:15 Mean=07:14 N=4	02:03-02:30 Mean=02:16 N=2
Cucumber - Picowell	2	*01:00**	*00:30**	11:00-18:00 Mean=14:18 N=4	00:30-03:30 Mean=01:14 N=9	*10:00**
Dwarf tomato - PAT orange	4	*01:00**	*01:00**	14:40-17:30 Mean=16:05 N=2	01:51-07:30 Mean=04:26 N=16	*10:00**
Dwarf tomato - Cherry	4	*01:00**	*01:00**	13:15 N=1	02:13-09:45 Mean=05:38 N=17	*10:00**

2. *Maintenance*

Maintenance tasks are system specific and dependent to a large degree on the architecture of the greenhouse. Around 15 minutes per day were required to perform a system and plant check either inside the FEG or remotely from the control interface in the NM III laboratory. During the 2018 season, the only task associated to the illumination subsystem of the FEG was to adjust the light intensity settings for the tomato, pepper, cucumber and basil plants when those grew taller. The crewtime associated to that task was in the order of minutes every few

[*] Not measured, but based on the experience of the on-site operator.

months. The atmosphere management subsystem required almost no maintenance throughout the season. The only tasks performed were the exchange of a coarse filter (~10 minutes crewtime) and two exchanges of CO_2 bottles (~1 hour 30 minutes, including transport of bottles between NM III and MTF).

Most of the maintenance tasks of the season were performed on equipment of the nutrient delivery subsystem (NDS). The EC and pH sensors of the two nutrient solution tanks were calibrated two times within the 9 months of operation. Each calibration event took around 1 hour and 30 minutes for all eight sensors. The subsystem worked with concentrated stock solution bottles, which contained the nutrient solution in several times the concentration of what was in the nutrient tanks themselves. The stock solution bottles were prepared by the on-site operator in the laboratory inside NM III by mixing different mineral fertilizers with DI water. During the around nine months of operation the NDS required 114 stock solution bottles. The preparation of one bottle required 8-11 minutes (mean=00:09:39, N=26) including preparation of equipment and cleaning. One component of the stock solution bottles was a mixture of micronutrients which needed to be prepared separately. One micronutrient mixture was sufficient for 20 stock solution bottles and took on average 00:17:30 (N= 2) crewtime. In total the preparation of nutrient stock solution bottles adds up to 20:05:06 during the around nine months of operation. The NDS also used diluted acid and base bottles to adjust the pH of the nutrient solutions. The preparation of one acid and base bottle took around 3 minutes. In total 30 minutes during the season.

The two NDS tanks needed to be emptied, cleaned and refilled during the season. This was required due to the formation of biofilms in the nutrient solution and signs of nutrient deficiency on the crops (mainly calcium and potassium). The whole procedure involves several working steps and requires around 5 hours of crewtime per tank. This procedure was executed seven times during the 2018 season.

The MTF does not have water supply and drainage connections to NM III. A fresh water tank and a waste water tank each with a capacity of around 250 liters are part of the MTF. The former is filled by bringing canisters containing DI water from NM III while the latter is emptied into canisters which are dumped into the water system of NM III. The water transpired by the plants is recycled and fed back to the fresh water tank in order to reduce water usage. Fresh water is used to top up the nutrient solution tanks with water build into the plants and for cleaning tasks. Waste water only is produced by cleaning tasks. Fresh water supply and waste water removal required around 01:30:00 crewtime per occurrence. Fresh water was supplied 14 times and waste water was removed 8 times during the season.

Cleaning tasks are also part of the maintenance tasks cluster. However, the crewtime for these tasks was not measured to great extent. Based on the records of the work performed during the 2018 season a crewtime of around 10:00:00 is assumed.

Table 3 summarizes the CT required for maintenance tasks during the 2018 season. The total amount of CT for maintenance tasks was 174:15:06 or 18:17:00 per month. Assuming that CT for maintenance tasks is proportional to the amount of trays inside the FEG, the maintenance CT per month per tray is 00:28:52 or 01:28:01 per month per square meter.

Table 3: Total CT for the season (286 days) and CT/month (1 month = 30 days) associated for maintenance tasks of the MTF.

	Daily system and plant check	**Illumination Subsystem**	**Atmosphere Management Subsystem**	**Nutrient Delivery Subsystem**	**Fresh and waste water**	**Cleaning tasks**
CT season total [h:min:s]	67:30:00	*02:00:00*[*]	03:10:00	58:35:06	33:00:00	*10:00:00*[*]
CT/month [h:min:s/month]	07:05:00	00:12:35	00:20:00	06:08:45	03:27:40	01:03:00
CT/day [h:min:s/day]	00:14:10	00:00:25	00:00:40	00:12:17	00:06:55	00:02:06

3. *Repair*

Crewtime spent on repair tasks was not tracked during the 2018 season. Although there were numerous off-nominal events which required the on-site operator to spend crewtime associated with this category, the exact amount of crewtime was not measured. Treating with the off-nominal event and bringing the MTF back to nominal operation by repairing or exchanging equipment was always more important than measuring the crewtime.

[*] Not measured, but assumed based on work reports.

4. Science

Tracking the crewtime for science tasks was only possible for a few routine tasks like sampling. Microbial surface sampling with swaps (20 locations, 4 swaps per location) inside the MTF took around 01:00:00 crewtime once a month. Plant sampling for microbial investigations (10 crops, 4 samples per crop) inside the FEG required around 01:10:00 per event once a month. Nitrate measurements (25 data points per crop produce of one harvest) of crop produce took around 01:05:00 to do. Other common scientific tasks during the 2018 season were the freeze drying of plant material, performing food safety tests with preconditioned test kits, questionnaires, food sensory panels, etc. which were not monitored in terms of crewtime.

D. Crewtime per crop output

The previous chapters explained the amount of crewtime required for certain task clusters and crops. When combining the different values for each crop, one can calculate the crewtime required per square meter per crop and also per kilogram of yield. The amount of crop cultivation tasks performed during one cultivation cycle is required for the calculation of $CT_{GH\_crop\_cultivation}$:

$$CT_{GH\_crop\_cultivation} = \sum_j (N_j * CT_j) \quad (3)$$

Where j is a specific task, N how often this task was performed in one cultivation cycle and CT the crewtime required for the task. The resulting values can be expressed per square meter. Table 4 shows these values for each crop species.

As mentioned before $CT_{GH\_maintenance}$ was 01:28:01 per month per square meter for the FEG during the 2018 season. This is equal to 00:02:56 per day per square meter. When multiplying this value with the average cultivation cycle one receives $CT_{GH\_maintenance}$ per cultivation cycle per cultivation area for each crop. CT_{GH} then is the sum of $CT_{GH\_crop\_cultivation}$ and $CT_{GH\_maintenance}$. These values are shown in Table 4 for each crop.

Lettuce and radish required by far the least amount of crewtime for crop cultivation tasks, because these crops were basically left alone between transfer to the cultivation trays and harvest. Leafy greens such as arugula, Swiss chard, red mustard and Mizuna required more crewtime, because of the spread harvesting method that was used. Spread harvesting in this case means that large mature leaves were cut from the plants at regular intervals. The plant was always left with a number of young leaves for regrowth. Herbs were also spread harvested, but here the harvesting process takes more time and occurs more often during the cultivation cycle. The long cultivation cycles and large amounts of tasks performed during the cultivation cycle result in the largest crewtime demand of the fruit forming crops cucumber and dwarf tomato.

Due to the different lengths of the crops' cultivation cycles an evaluation is only possible when the CT_{GH} values are time normalized over the respective average cultivation cycle of each crop. The results are shown in Table 4 and Figure 1. It is evident, that the difference between the lowest and highest CT_{GH} value is reduced because of the normalization. Lettuce has the lowest normalized crewtime value. The highest value is now on Mizuna and not on dwarf tomatoes.

Table 4: Values for amount of tasks per cultivation cycle, cultivation cycle and crewtime for various crops.

Crop	Sowing	Transfer	Pruning	Harvest	Average culti-vation cycle [d]	$CT_{GH\_crop\_cultivation}$ per cultivation cycle per cultivation area [h:min:s/m²]	$CT_{GH\_maintenance}$ per cultivation cycle per cultivation area [h:min:s/m²]	CT_{GH} per cultivation cycle per cultivation area [h:min:s/m²]	CT_{GH} per cultivation area time normalized [h:min:s/m²/d]
Lettuce - Batavia	1x	1x	0x	1x	37.8 N=16	00:21:27	01:50:53	02:12:20	00:03:30
Lettuce - Expertise	1x	1x	0x	1x	37.8 N=16	00:21:27	01: 50:53	02:12:20	00:03:30
Lettuce - Outredgeous	1x	1x	0x	1x	37.6 N=14	00:21:27	01: 50:23	02:11:50	00:03:30
Lettuce - Waldman's Green	1x	1x	0x	1x	37.7 N=12	00:21:27	01: 50:53΄7	02:11:54	00:03:30
Swiss Chard	1x	1x	0x	7x	90 N=3	03:02:10	04:23:55	07:26:05	00:04:57
Red Mustard - Red Giant	1x	1x	0x	6x	79.8 N=4	02:16:17	03:53:52	06:10:09	00:04:38
Red Mustard - Frizzy Lizzy	1x	1x	0x	5x	79.8 N=4	02:08:33	03:53:52	06:02:25	00:04:33

Crop	Sowing	Transfer	Pruning	Harvest	Average culti-vation cycle [d]	$CT_{GH\_crop\_cultivation}$ per cultivation cycle per cultivation area [h:min:s/m²]	$CT_{GH\_maintenance}$ per cultivation cycle per cultivation area [h:min:s/m²]	CT_{GH} per cultivation cycle per cultivation area [h:min:s/m²]	CT_{GH} per cultivation area time normalized [h:min:s/m²/d]
Mizuna	1x	1x	0x	14x	119 N=1	08:29:27	05:48:58	14:18:25	00:07:13
Arugola	1x	0x	0x	1x	28.1 N=17	01:35:50	01:22:17	02:58:07	00:06:21
Parsley	1x	0x	0x	22x	286 N=1	10:24:23	13:00:02	23:24:25	00:05:17
Chives	1x	0x	0x	28x	286 N=1	05:25:37	13:00:02	18:25:38	00:04:05
Basil - Dolly	1x	1x	0x	9x	121 N=2	04:57:43	05:54:50	10:52:43	00:05:24
Radish - Raxe	1x	1x	0x	1x	23.3 N=8	00:44:12	01:08:11	01:52:23	00:04:50
Cucumber - Picowell	1x	1x	7x	28.5x	161 N=2	07:27:25	07:52:07	15:19:32	00:05:43
Dwarf tomato - PAT orange	1x	1x	6x	20.5x	286 N=2	10:07:53	13:58:41	24:06:33	00:05:03
Dwarf tomato - Cherry	1x	1x	5x	24x	286 N=2	10:50:46	13:58:41	24:49:26	00:05:12

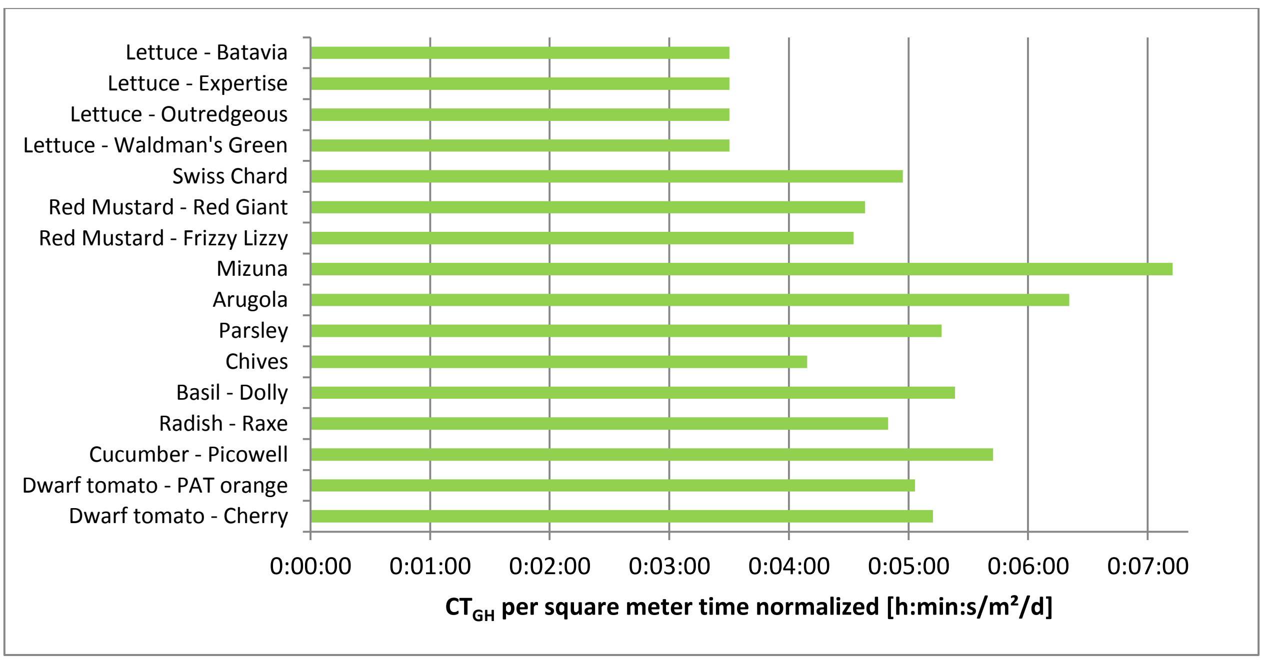

Figure 1: Time normalized CT_{GH} per cultivation area.

While the normalized CT_{GH} per cultivation area gives some insight into the crewtime required per square meter in general when cultivating a certain crop, it should not be used for plant selection or other comparative analysis. The crewtime needs to be put in perspective of the yield of the different crops to do such a comparison. Therefore the average yield is required per crop. These values were measured per tray (0.328 m²) and are shown in Table 5.

When dividing the CT values in Table 4 by the yield per square meter one receives the crewtime per kilogram of edible biomass for the plant cultivation tasks, the maintenance tasks and the total CT_{GH}. The lower this value the better is the performance of the crop in terms of crewtime demand. Consequently, cucumber was the best performing crop in terms of crewtime during the 2018 season of the EDEN ISS FEG, see Figure 2. Leafy greens and some lettuce varieties require relatively small amounts of crewtime (<40 minutes) per kilogram. Herbs, radish, Batavia lettuce and dwarf tomato plants required the most crewtime per produced kilogram of edible biomass.

Table 5: Average yield and crewtime per yield values for various crops.

Crop	Average yield per cultivation cycle per tray [kg]	Average yield per cultivation cycle per cultivation area [kg/m²]	$CT_{GH\_crop\_cultivation}$ per yield [h:min:s/kg]	$CT_{GH\_maintenance}$ per yield [h:min:s/kg]	CT_{GH} per yield [h:min:s/kg]
Lettuce - Batavia	0.51 N=16	1.56	00:13:43	01:10:58	01:24:41
Lettuce - Expertise	0.78 N=16	2.38	00:09:00	00:46:34	00:55:35
Lettuce - Outredgeous	0.69 N=14	2.11	00:10:09	00:52:30	01:02:39
Lettuce - Waldman's Green	0.95 N=12	2.89	00:07:26	00:38:25	00:45:50
Swiss Chard	3.04 N=3	9.26	00:19:40	00:28:30	00:48:10
Red Mustard - Red Giant	3.22 N=4	9.82	00:13:53	00:23:50	00:37:43
Red Mustard - Frizzy Lizzy	2.63 N=4	8.01	00:16:03	00:29:11	00:45:13
Mizuna	7.58 N=1	23.11	00:22:03	00:15:06	00:37:09
Arugola	1.33 N=17	4.07	00:23:34	00:20:14	00:43:48
Parsley	5.40 N=1	16.46	00:37:56	00:47:23	01:25:19
Chives	4.58 N=1	13.97	00:23:19	00:55:50	01:19:09
Basil - Dolly	2.39 N=2	7.30	00:40:49	00:48:38	01:29:27
Radish - Raxe	0.51 N=8	1.55	00:28:34	00:44:03	01:12:37
Cucumber - Picowell	16.69 N=4	50.88	00:08:48	00:09:17	00:18:04
Dwarf tomato - PAT orange	4.29 N=2	13.06	00:46:32	01:04:13	01:50:43
Dwarf tomato - Cherry	4.89 N=2	14.90	00:43:40	00:56:17	01:39:57

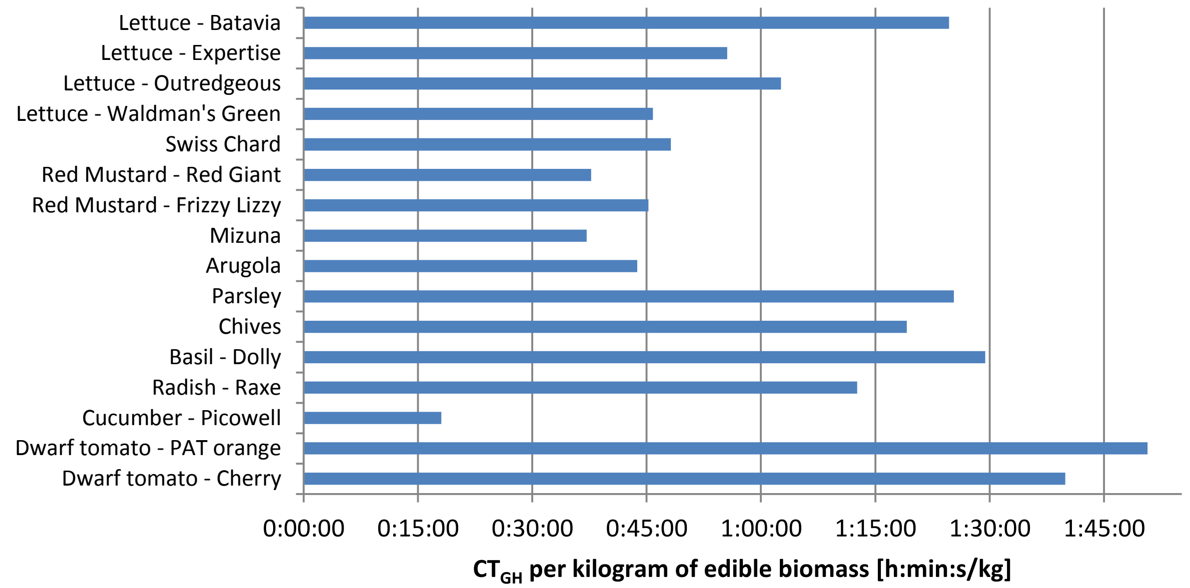

Figure 2: CT_{GH} normalized per kilogram of produced biomass.

VI. Discussion

The EDEN ISS MTF is a space analogue test side for a space greenhouse and therefore, suitable to do investigations in the crewtime demand of a space greenhouse. Some aspects of the crewtime use, especially the maintenance component, depend strongly on the system architecture and chosen components. Consequently, the values presented in this paper can only give some implications for the crewtime demand of a future space greenhouse.

The crewtime measurements taken during the 2018 wintering season presented in Table 2 and Table 3 are the first of such measurements performed in the EDEN ISS MTF. The amount of measurement events was limited due to the available working time of the on-site operator during this season. Therefore, some assumptions based on the experience of the on-site operator and based on the work reports were made to complement the measurement data. This means that the calculations and results in this paper depend to a relatively large degree on those assumptions.

The results of this paper also have implications on crop selection procedures for future space greenhouses. Crops with a high yield and a low crewtime demand are more favorable than those with a large crewtime demand. This needs to be taken into account as one of the various factors for the crop selection.

VII. Summary

The EDEN ISS MTF successfully went through its first year of operation in Antarctica in the vicinity of the German Neumayer III station. More than 200 kilograms of fresh vegetables were harvested and numerous experiments were performed by the on-site operator. One of the experiments was about getting a better understanding on how much crewtime is required to grow plants in a space greenhouse. The results of this investigation are presented in this paper. The crewtime demand of a space greenhouse is comes from working with the plants, maintaining the system functionality, doing repairs and executing scientific tasks. It was shown that the crewtime required to maintain the systems is larger than the crewtime required for the tending of the plants. Consequently, there is also the greatest potential to reduce the crewtime demand of a plant cultivation system. Plants with a high yield and low crewtime demand are generally to be prepared in a future space greenhouse. From the crops grown during the 2018 season of the EDEN ISS MTF, cucumber has the lowest crewtime value per kilogram yield. Some leafy greens and lettuce varieties also have relatively low values, whereas herbs, dwarf tomatoes and radish are the least efficient crops.

Further research and measurements are required to solidify the results presented in this paper. Measurements also need to be done with other crop species (e.g. grains and legumes) to complement the data presented in this paper. The EDEN ISS project team foresees to continue the crewtime measurements in the 2020 wintering season. The authors plan to use specified devices such as timeular (https://timeular.com/) to improve the measuring of the crewtime, which when done manually is time consuming by itself.

Appendix

Table 6 and Table 7 show four exemplary workdays in the EDEN ISS MTF in the 2018 wintering season. Only the timespan from the beginning of breakfast to the end of dinner is listed. The remaining time of the day was used for leisure activities and sleeping.

Table 6: Greenhouse CT workday data day A and day B.

Day A - August 14th, 2018			
Start time	**End time**	**CT [min]**	**Task**
09:00	09:30	30	Breakfast
09:30	10:00	30	Preparation of MTF supplies
10:00	10:20	20	Cloth changing, walk to MTF, cloth changing
10:20	10:40	20	ISPR plant cultivation system check
10:40	11:48	68	Harvesting of crops
11:48	11:56	8	Sowing of crops
11:56	12:10	14	Cloth changing, walk to NM III, cloth changing
12:10	13:00	50	Lunch
13:00	15:00	120	Contact with mission control
15:00	15:15	15	Break
15:15	15:50	35	Harvest processing
15:50	16:10	20	Food quality and safety sampling
16:10	17:00	50	Food safety sample preparation
17:00	18:00	60	Office work
18:00	18:30	30	Free time
18:30	19:30	60	Dinner
19:30			Free time

Day B - October 19th, 2018			
Start time	**End time**	**CT [min]**	**Task**
08:45	09:00	15	Breakfast
09:00	09:15	15	Office work
09:15	09:30	15	Preparation of MTF supplies
09:30	09:50	20	Cloth changing, walk to MTF, cloth changing
09:50	10:10	20	Daily system and plant check
10:10	10:49	39	Harvesting of crops
10:49	10:55	16	Nursery and radish transfer
10:55	11:18	23	Cloth changing, walk, to NM III, cloth changing
11:18	11:25	7	Harvest processing
11:25	11:30	5	Break
11:30	11:43	13	Preparation of freeze drier
11:43	12:14	31	Preparation of samples for freeze drying
12:14	13:00	46	Lunch
13:00	13:45	45	Contact with mission control
13:45	15:55	130	Nitrate measurements
15:55	16:05	10	Micro Biological Survey (MBS) test kits result documentation
16:05	16:30	25	Office work
16:30	18:30	120	Free time
18:30	19:30	60	Dinner
19:30			Free time

Table 7: Greenhouse CT workday data day C and day D.

Day C - September 07th, 2018			
Start time	**End time**	**CT [min]**	**Task**
09:15	09:30	15	Breakfast
09:30	10:00	30	Cloth changing, walk to MTF
10:00	10:20	20	Shoveling snow in front of entrance
10:20	10:30	10	Cloth changing, unpacking of supplies
10:30	10:40	10	Leak sensor check
10:40	10:50	10	ISPR check
10:50	11:40	50	Harvesting of crops

Day D - November 6th, 2018			
Start time	**End time**	**CT [min]**	**Task**
09:15	09:30	15	Breakfast
09:30	09:45	15	Subsystem telemetry check
09:45	10:30	45	Cloth changing, transport CO_2 and filters to MTF
10:30	10:45	15	Unpacking supplies, cloth changing
10:45	11:00	15	Measuring heater dimensions
11:00	11:05	5	Cleaning tray lids
11:05	11:10	5	Lettuce transfer from nursery to trays

Day C - September 07th, 2018			
Start time	**End time**	**CT [min]**	**Task**
11:40	11:48	8	Miscellaneous subsystem checks
11:48	12:07	19	Cloth changing
11:57	12:07	10	Shoveling snow from platform
12:07	12:22	15	Walk to NM III, cloth changing
12:22	13:36	74	Lunch
13:36	13:49	13	Office work
13:49	14:15	26	Cloth changing, walk to MTF
14:15	14:28	13	Leak sensor exchange
14:28	14:40	12	Sowing 20x lettuce, 10x tomato
14:40	14:53	13	Transfer Kohlrabi
14:53	14:58	5	Tomato transfer
14:58	15:09	11	Pruning Tomato - Bogus Fruchta
15:09	15:30	21	Pruning Pepper - Cupid
15:30	15:42	12	Removal Pepper - 1601-M
15:42	16:07	25	Lettuce harvest
16:07	16:30	23	Packing of harvest, cloth changing
16:30	16:50	20	Walk to NM III, cloth changing
16:50	17:20	30	Break
17:20	18:30	70	Harvest processing
18:30	19:30	60	Dinner
19:30			Free time

Day D - November 6th, 2018			
Start time	**End time**	**CT [min]**	**Task**
11:10	11:15	5	Nursery cleaning
11:15	11:18	3	Cucumber side shoot pruning
11:18	12:05	47	Cloth changing, transport empty CO_2, drive to NM III, cloth changing
12:05	12:35	30	Lunch
12:35	13:05	30	Office work
13:05	14:05	60	Meeting (phone call)
14:05	14:30	25	Cloth changing, drive to MTF, cloth changing
14:30	16:35	125	Harvesting of crops
16:35	16:45	10	Cloth changing, drive to NM III, cloth changing
16:45	17:00	15	Support other crew members
17:00	17:30	30	Harvest processing
17:30	17:40	10	Daily station briefing
17:40	18:00	20	Support of other crew members
18:00	18:30	30	Dinner
18:30			Free time

Acknowledgments

The EDEN ISS project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 636501.

References

[1]Bamsey, M., Zabel, P., Zeidler, C., Poulet, L., Schubert, D., et al., “Design of a containerized greenhouse module for deployment to the Neumayer III Antarctic Station,” *44th International Conference on Environmental Systems,* Tucson, Arizona, 2014.

[2]Bamsey, M., Zabel, P., Zeidler, C., Vrakking, V., Schubert, D., et al., “Early Trade-offs and Top-Level Design Drivers for Antarctic Greenhouses and Plant Production Facilities,” *46th International Conference on Environmental Systems,* Vienna, Austria, 2016.

[3]Vrakking, V., Bamsey, M., Zabel, P., Zeidler, C., Schubert, D., et al., “Service Section Design of the EDEN ISS Project,” *47th International Conference on Environmental Systems,* Charleston, South Carolina, 2017.

[4]Zabel, P., Bamsey, M., Zeidler, C., Vrakking, V., Johannes, B.-W., et al., “Introducing EDEN ISS - A European project on advancing plant cultivation technologies and operations,” *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

[5]Zabel, P., Bamsey, M., Zeidler, C., Vrakking, V., Schubert, D., et al., “The preliminary design of the EDEN ISS Mobile Test Facility - An Antarctic greenhouse,” *46th International Conference on Environmental Systems,* Vienna, Austria, 2016.

[6]Zabel, P., Bamsey, M., Zeidler, C., Vrakking, V., Schubert, D., et al., “Future Exploration Greenhouse Design of the EDEN ISS project,” *47th International Conference on Environmental Systems,* Charleston, South Carolina, 2017.

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

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

[9]Anderson, M. S., Ewert, M. K., Keener, J. F., and Wagner, S. A., "Life Support Baseline Values and Assumptions Document," *NASA,* NASA/TP-2015–218570, 2015.

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

[11]Russell, J. F., Klaus, D. M., and Mosher, T. J., "Applying Analysis of International Space Station Crew-Time Utilization to Mission Design," *Journal of Spacecraft and Rockets*, Vol. 43, No. 1, 2006, pp. 130–136.

[12]Gitelson, I. I., Lisovsky, G. M., and MacElroy, R. D., *Manmade closed ecological systems,* Taylor & Francis, London, New York, 2003.