Estimate of the environmental impact of the ELT instrument MOSAIC

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ABSTRACT

MOSAIC is an instrument for the Extremely Large Telescope (ELT). The instrument has started phase B, and apart from technical and financial requirements, MOSAIC has the additional requirement to investigate and minimise its environmental impact. The first step is to estimate the carbon footprint (and other effects) in a 'Life Cycle Analysis', for the instrument development up to Provisional Acceptance in Chile. This paper presents a preliminary analysis, aimed at identifying potential contributors to environmental impact. Investigated contributors are: materials, Full-Time-Equivalents, travel, and transport of the instrument. Not yet investigated (due to lack of information or certainty) are: electronics, test facilities and prototyping. Uncertainty in input data and conversion factors leads to error bars of a factor 2 or larger. Therefore, the outcome of the analysis can be used for internal comparison of contributors only, and it should not be used for comparison to other instruments or disciplines.

Keywords: ELT instrument, MOSAIC, sustainability, environmental impact, Life Cycle Analysis

1. INTRODUCTION

1.1 The reason behind the analysis

The environmental conditions at earth have been very stable for around 10.000 years, but they are now changing due to human activity. Papers 1 and 2 describe for nine processes the 'planetary boundaries' within humanity can operate safely, without causing irreversible changes to these processes. Climate change is one of the processes that receives much attention, but there are more. The nine processes are (as defined by 2 in 2023) : climate change; novel entities, rate of biodiversity loss; interference with the nitrogen and phosphorus cycles; stratospheric ozone depletion; ocean acidification; global freshwater use; change in land use; and atmospheric aerosol loading. Climate change, rate of biodiversity loss, novel entities, change in land use, global freshwater use and interference with the nitrogen and phosphorus cycles are outside the safe region. By doing a LCA, the hope is to find ways to reduce the impact of our instrument development on these processes.

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1.2 Introduction MOSAIC

MOSAIC is an instrument for the Extremely Large Telescope (ELT) . The instrument has started phase B in early 2023; a description of the instrument is given in 3. Apart from technical and financial requirements, MOSAIC is the first ESO instrument with the additional requirement to investigate and minimise its environmental impact. The first step is to estimate the carbon footprint (and other effects) in a 'Life Cycle Analysis' (LCA), for the instrument development up to Provisional Acceptance (PAC) in Chile.

MOSAIC has a sustainability committee consisting of 5 persons, who do analyses based on input from the technical team, and who can give recommendations to the project office. The committee has decided that to guide the project, we would begin by using the LCA to understand our uncertainties in estimating the environmental impact and then begin to assess strategies and scenarios that could lead to mitigation without affecting the core technical performance or introducing significant, additional costs. In other words, we provide guidance based on assessment which is compatible with the other drivers in the project and so sustainability becomes part of the design and engineering disciplines.

The Life Cycle Analysis of several other instruments have been done, and these serve as a source of information and comparison. 4 discusses the Life Cycle Analysis of the Athena X-ray Integral Field Unit. The European Southern Observatory (ESO) has had a Life Cycle Analysis done for the GRAAL instrument (5). We can use several aspects of that latter analysis for MOSAIC; for example, the average environmental impact of 1 FTE (Full Time Equivalent) at ESO Garching. The main difference is that the MOSAIC analysis is done early in the project, whereas in case of GRAAL the analysis was done afterwards. Doing the analysis early in the project gives the opportunity to identify the main contributors to environmental impact and actively steer the project towards sustainable solutions.

2. PURPOSE AND STATUS OF THE ANALYSIS

There are two sources of significant uncertainty in the outcome of the analysis:

- uncertainty in the input data (amount of materials to be used / travels made / energy used).
- uncertainty in the conversion factors from input data to environmental impact.

Yet the calculation is useful if the estimates can be used for comparing the environmental impact of several scenarios within the uncertainties stated.

The current status of the analysis is summarised in Figure 1. The analysis includes the project phases up to Provisional Acceptance in Chile (PAC), as defined in our Statement of Work. Nevertheless, the impact from operations and de-commissioning could be significant and it would be interesting to investigate those as well.

2.1 Databases with conversion factors

The analysis requires a database to convert input parameters (kilometers travelled, kg of material used) to output (liters of water used, kg of CO2-equivalents emitted, etc). We have access to the following databases / calculators :

- Ecoinvent is a commercial database. It contains many inputs (materials, energy, transport, processes), and many outputs (climate change, terrestrial acidification, aquatic ecotoxicity, land occupation, terrestrial ecotoxicity, ionising radiation, respiratory effects, human toxicity, ozone layer depletion, photochemical oxidation, non-renewable energy, mineral extraction, aquatic eutrophication, aquatic acidification). The educational license costs 3800 Euros, plus a 750 Euro yearly maintenance fee. For the GRAAL project 5 , the most relevant lines were extracted from the database, and these are available. We can thus experiment with a subset of the ecoinvent database. The environmental effects are given in both physical units and scaled to so called 'points', to allow comparison of several environmental effects.

Occasion	Estimated Value / Status
Phase B - up to PDR	
FTE	170
Travel	data collected, analysis done
Phase C - between PDR and FDR	
FTE	190
Travel	data collected, analysis done
Materials for prototypes	Not yet investigated
Test facilities	Not yet investigated
channel MAIT - between FDR and CDR	
FTE	280
Travel	data collected, analysis done
Materials for final hardware	data collected, analysis done
Test facilities	Not yet investigated
PAE - between CDR and PAC	
FTE (EU and Chile)	90
Travel	data collected, analysis done
Test facilities	Not yet investigated
Instrument transport	3 scenarios investigated : boat + truck boat + rail + truck flight + truck
Commissioning and operations - until end-of-life	
FTE (EU and Chile)	20
Travel	data collected, analysis done
consumables during instrument operation (Electricity, LN2)	Not yet investigated
Data storage	Not yet investigated
Disposal	Not yet investigated

Figure 1. Identified contributions to the instrument environmental impact. The part after Provisional Acceptance Chile (PAC) is not officially part of the analysis, and hence light shaded.

- ADEME offers a free database. It contains many inputs (materials, energy, transport, processes), and many outputs (ozone layer depletion, aquatic eutrophisation, terrestrial eutrophication, photochemical ozone formation, particular matter, ionising radiation, minerals and metal resource use, land use). The outputs are given in physical units. Although quite complete, the database does not always contain an applicable entry. There are for example many entries regarding 'steel', however most are 'steel in household electronics, subsitution benefits included'. Including the 'substitution benefits' results in a negative carbon footprint, which is not what one expects for a raw material. The closest match to steel as a raw material was 'steel unspecified, for furniture', and the closest match to aluminium as a raw material was 'sheet' or 'extrusion profile'. The ADEME database was in the end not used for calculating the impact from materials.
- IRAPs travel-footprint-calculator calculates the CO2-eq emission of air travel.

- Ecopassenger compares the CO2-eq emission of several travel options including car, train, and air travel.
- Circulairecijfers 6 is a free database that lists CO2-eq emission, energy use, and water use, for the production of raw materials.

These databases and calculators were compared to each other, based on their output CO2-eq emission (the only common parameter among all these databases). As table 1 and 2 show, there are sometimes large differences. In case of the train, these are caused by differences among countries, in case of the flight, these are caused by taking radiative forcing into account or not. (see reference 7) By taking an average and producing an uncertainty, we quantify both a usable average which converges on a European average for rail–relevant for MOSAIC since the bulk of those project members traveling by this mode are all based in Europe–and for flights represents a value which embraces the complex uncertainties in feedbacks and additional forcings by this mode of transport.

Table 1. Conversion factors for train, air, bus, and car travel. In case different values were given for short-haul, medium-haul, and long-haul flights, the medium-haul value is taken. The contrails produced by airplanes cause climate change, usually a factor ~ 2 is used to correct for this, but it is an uncertain number.

Database	Train factor CO2eq kg/km	Flight factor CO2eq kg/km	Bus factor CO2eq kg/km	Car factor CO2eq kg/km	Comments
ADEME (DE)	0.002-0.08	0.1-0.14	0.03	0.22	flight without radiative forcing from contrails
Ecoinvent (DE)	0.07	0.1	0.11	0.33	flight without radiative forcing from contrails
IRAP (FR)	0.023	0.17-0.30	-	-	
Ecopassenger (UK)	0.017	0.24	-	0.17-0.23	
Average	0.037	0.175	0.07	0.25	

Table 2. Conversion factors for raw materials

Database	Aluminium CO2eq kg/kg	Steel CO2eq kg/kg	Glass CO2eq kg/kg
ADEME	3.2232	1.5109	1.6172
Ecoinvent	7.6038	5.167	1.0756
Circulaire Cijfers	7.83	2.3	2.3

3. DATA COLLECTION AND ANALYSIS

3.1 Travel

All project managers and the board members were asked to list their travels for the project from the start of phase B (March 2023) until April 2024, and to estimate their travel until the end of the project. The travelled distance, transport means (car, train, bus, plane), and the number of hotel nights were collected. In several cases, the impact of accommodation can be equal to travel (see e.g. reference 8 for the magnitude of values. We use 34 kg CO2-eq per night, see 5) hence we include this factor in our travel calculations.

Adding up all expected and already realised travel from the start of phase B up to PAC, results in : $\sim 4 \times 10^5$ km train, $\sim 3 \times 10^3$ km bus, $\sim 2 \times 10^4$ km car and $\sim 2 \times 10^6$ km flight, and $\sim$ 1700 nights in a hotel.

The related estimated CO2-eq emission, based on the average conversion factors in table 1 is $\sim 3 - 4 \times 10^5$ kg , of which 10-20 % is caused by overnight stays.

3.2 FTE

A Full Time Equivalent is one person working full time for one year. It comes with an environmental impact from commuting, a work desktop / laptop, the canteen, heating the institute, etc. This impact could well differ significantly from institute to institute. But with 31 Institutes in the MOSAIC consortium, we did not attempt to calculate this for each institute separately. Instead, the conversion factor for 1 FTE at ESO in Garching is taken from the GRAAL report, which uses the ecoinvent database: 3400 kg CO2-eq / FTE. This number includes staff commute, office heating, office electricity, office amortizement, staff consumables, and waste. The report also gives a number for an FTE in Paranal, but this is not relevant for our analysis as by far most of the FTEs up to PAC are spent in Europe.

Table 3 shows an estimate of the amount of FTE required per project phase. The total is 750 FTE (lower limit). This results in a $\sim 2.5 \times 10^6$ kg CO2 equivalent emission related to FTEs. This is a very uncertain number; we expect the actual emission to be between 25% and 200% of this number.

Table 3. Estimate of FTE per project phase, as of now.

Phase	Year	Year	FTE
KO	Q1 2023	2023	10
SAR	Q4 2024	2024	40
		2025	50
PDR	Q4 2026	2026	70
		2027	90
FDR	Q4 2028	2028	100
		2029	100
		2030	100
MAIT	Q4 2031	2031	80
PAE	Q4 2032	2032	50
		2033	40
PAC	Q4 2034	2034	20
Total			750

3.3 Materials

The technical team made an initial estimate of the amount of (raw) materials in the final instrument, and used for AIT tools, see Figure 2. Our ecoinvent database was used to translate this into environmental impact. Because it does not include conversion factors for carbon fiber, the carbon footprint for carbon fiber was taken from circulaire cijfers. Moreover, 'electronics' is excluded from the analysis, because ecoinvent has separate entries for 'active electronic component' and 'passive electronic component', with quite different impacts. We do not yet have detailed enough information to calculate the impact from electronics.

Apart from the mass of the materials going into the final instrument plus what is used for AIT tools, more material is needed for prototyping and manufacturing.

- Prototyping is not taken into account. Although some prototypes have been defined (for example, for testing the distributed AIV) the list may not yet be complete.
- No correction factor for spares or manufacturing losses has been applied.

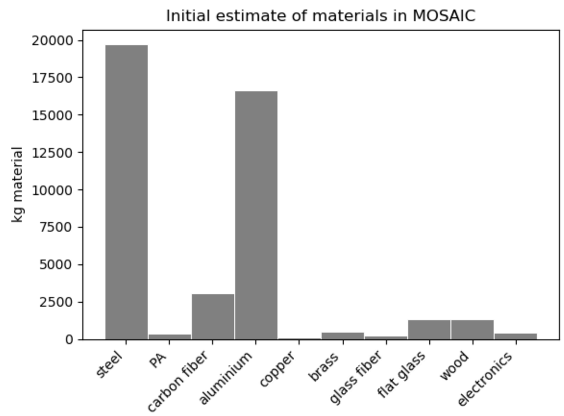

Figure 2. Initial estimate of the amount of raw materials, tools and electronics in MOSAIC.

3.4 Transport of instrument

The MOSAIC instrument consists of several systems, being: the visible channel (fibers and spectrograph), the near-infrared channel (fibers and spectrographs), Electronic Instrument Control System (EICS), Ground Layer Adaptive Optics (GLAO), and finally the front-end including Instrument Core Optical System (ICOS), optical relay system, fiber positioner, calibration unit, instrument support structure, and cable de-rotator . Figure 3 shows the instrument at the ELT Nasmyth platform. All subsystems have to be transported to Cerro Armazones in Chile. The ICOS system is being designed and manufactured in Brazil, and it would save a lot of effort, risk, and environmental impact, if this system could be tested in Brazil and then shipped directly to Chile.

Three Transport scenarios were investigated, as summarised in Table 4. All assume the transport routes as shown in figure 5. In short, the systems are being integrated and tested at the institutes of the managing consortium partner for that system. Then all, except for ICOS, are shipped to LAM in Marseille, for preliminary acceptance in Europe. Some mass dummies will have to be shipped to Brazil, in order to test the ICOS subsystem. Then all systems are shipped to Chile. This can be done in the following ways :

- Scenario 1 : Truck + Rail + Boat.
- Scenario 2 : Truck + Boat.
- Scenario 3 : Truck + Flight. The flights in this scenario are from Groningen-Marseille, Madrid-Marseille, Newcastle (U.K.)-Marseille, Barcelona-São Paulo, Barcelona-Madrid-Viru Viru, and Sao Paulo - Viru Viru Airport - Cochabamba.

3.5 Total

Figure 6 shows an overview of the CO2-equivalent footprint of the contributors that were investigated. The error bars show the range where the actual emission (equivalent) is expected. These error bars are at least a factor 2, and larger if we think that is appropriate. In particular:

- for materials, the ADEME and ecoinvent resulted in a an outcome of more than a factor 2 difference.
- FTE is strongly country- and institute-dependent.

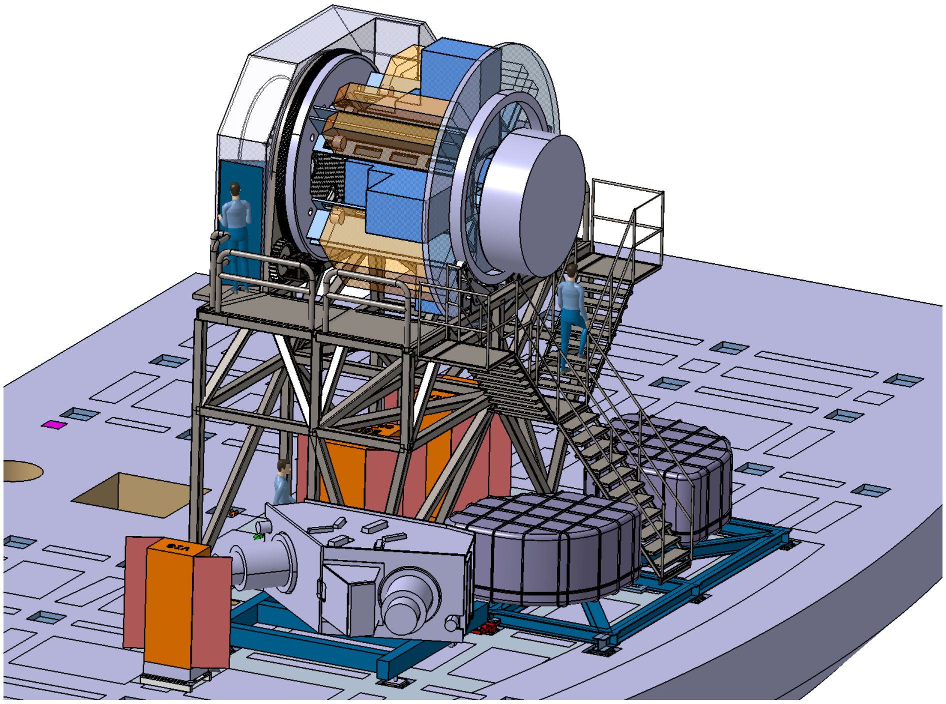

Figure 3. MOSAIC at the telescope.

	Sub-sytem	Mass (tons)	Route		Distances considering transportation mode (kms)						
					Truck+Rail+boat (1)			Truck+boat / only Truck (2)		With flight (3)	
					Truck	Rail	Boat	Truck	Boat	Truck	Flight
AIT	**VIS**	**7,67**	Netherlands	Marseille	20	1400	0	1300	0	60	1200
	NIR	**8,27**	Madrid	Marseille	30	1200	0	380	653	30	892
	GLAO	**0,8**	Durham	Marseille	20	1620	0	1650	0	60	1573
	ICOS dummies	**4,2**	Marseille	Itajuba	20	350	9200	280	9200	700	9400
AIV	**Part 1 to Chile**	**23**	Marseille	Armazones	142	1500	13379	1200	13379	2000	9600
	ICOS to Chile	**12,9**	Itajuba	Armazones	142	4156	0	3695	0	1350	1500

Figure 4. Overview of transport scenarios and masses to be transported.

4. CONCLUSION

An order-of-magnitude calculation shows that material, FTEs and Travel have a similar CO2-eq impact. Transport of the instrument could be similar or an order-of-magnitude lower, depending on the chosen transport strategy. Other contributors, like running lab facilities in the MAIT phase, have not yet been investigated.

This paper only publishes the CO2-eq emission of the instrument development, although the databases also provide numbers on other environmental effects (like ozone layer depletion, ionising radiation, land use, etc). Once we have gained more confidence in the accuracy of the outputs of other environmental effects, we can also think of strategies to minimise these.

Although this analysis can be used to track the environmental impact of the instrument over time, it should not be used for comparison to other instruments or fields, simply because the uncertainties are too large. On top of uncertainties in the input data, the outcome depends on the database of choice. If a more detailed analysis is needed, this requires more resources (skill, people, money for licenses).

Knowing that travel is an important impact, the committee and the project office already took measures to reduce the amount of people travelling to progress meetings, without hampering the communication within the team.

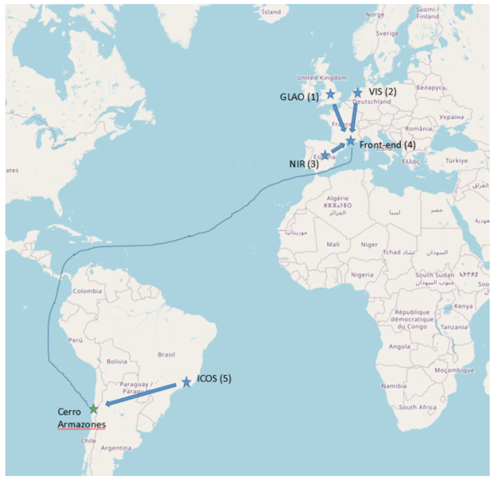

Figure 5. Transport routes of the instrument subsystems to the Extremely Large Telescope on Cerro Armazones.

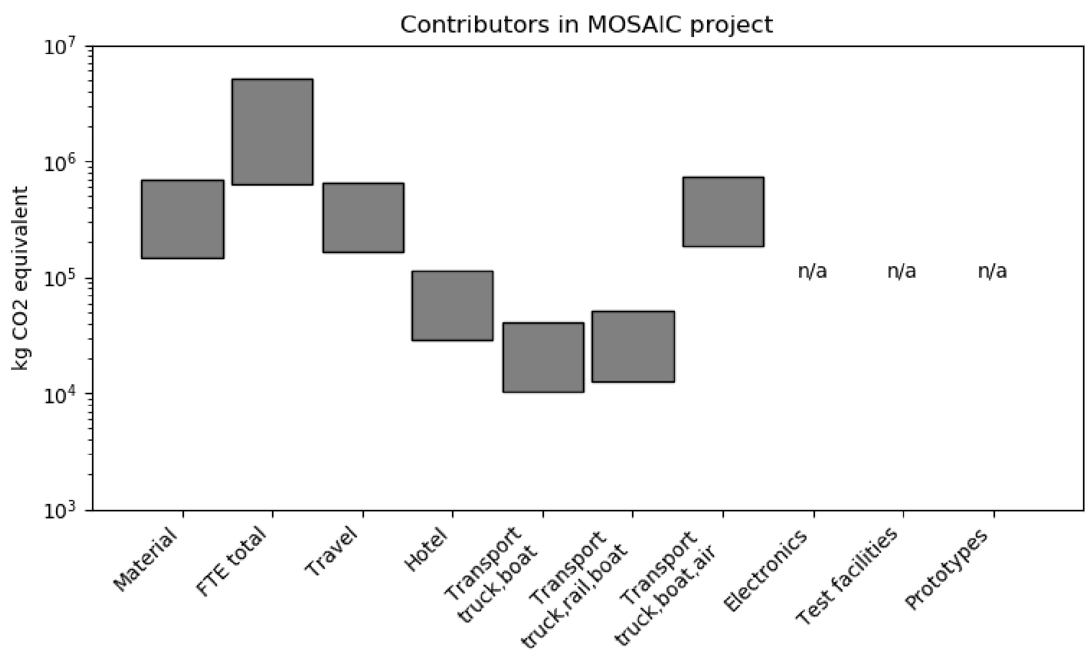

Figure 6. Overview of contributors to the total CO2-equivalent footprint. Values for electronics, test facilities and prototypes still need investigation.

Disclosures

The authors have no relevant financial interests in the manuscript and no other potential conflicts of interest to disclose.

Code, Data, and Materials Availability

The ecoinvent database is available only with a license. The Graal report 5 is not available online. Please contact the authors if you are interested, we need to discuss with ESO and the author if we can share the report.

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