ECODESIGN FOR SPACE AND AEROSPACE: WHAT HAPPENS WHEN WE MAKE ECODESIGN RELEVANT FOR DEMANDING APPLICATIONS?

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ABSTRACT

Introduction

Ecodesign and quantitative environmental scores from life-cycle assessment (LCA) are acknowledged elements in cleaner production. With the support of environmental information from LCA, ecodesign provides a structure to identify the major environmental challenges of existing manufacture practices, and potential trade-offs from novel technology. Life-cycle assessment is an established method to develop quantitative scores for a wide array of environmental risks over the life cycle of products and systems, often called a cradle to grave perspective.

The scope and methods of LCA is becoming cornerstone to environmental regulation, leading to a multitude of tools for environmental scoring, life cycle assessment or ecodesign guidelines. However, existing tools are specific to technology or application, with emphasis being mainly on products for public consumption and large-scale production practices. In this paper, we describe the challenges in adapting ecodesign tools for a demanding application such as the space and aerospace industry. These are industries that make use of non-standard materials and advanced manufacture processes, most often not covered by current ecodesign tools.

Methods

We describe here cases based on ongoing work for the European space industry, for the development of life-cycle based environmental scoring information for propellants, materials, components and manufacturing processes for space systems. Outcomes will be applied in the European Space Agency (ESA) Clean Space initiative. Many of the materials and processes are used also in aerospace, and findings are transferrable to the aerospace industry.

The cases apply a cradle-to-gate life-cycle perspective, meaning that environmental aspects of core materials and manufacturing processes are evaluated from primary raw material extraction up to the factory gate. The results of the study provides an insight into how resource use and emissions occur within the supply chain of core elements for demanding applications. Complete descriptions are available elsewhere [1]. Our aim is to identify the differences between ecodesign for the consumer-oriented context and for demanding applications, and extract lessons for developing ecodesign tools for the space, aerospace and other industries that use specialty materials and advanced manufacturing practices.

Cases in the full report cover specialty alloys of aluminium and titanium, glass and carbon fiber reinforced polymers, honeycomb structures, additive manufacturing techniques, photovoltaics, batteries, harness and electronic components for space, as well as traditional welding and machining operations, and heat

treatments. Tank production and nozzle extension are also included, as examples of use of the manufacturing datasets. This paper presents caresuts for aluminium alloys, thermoplastics (PEEK, PEI, PPS), photovoltaic cell (GaInP/GaAs on Ge wafer), direct metal laser sintering, and tank production.

Results and conclusions

Based on examples from developing the basis for ecodesign for space systems, some central conclusions to be drawn for when adapting ecodesign for demanding applications:

i) Materials used in demanding applications are not covered by current tools. Alloying elements for specialty metals, and precursor use in thermoplastic production, need to be covered by ecodesign tools.
ii) Specialized materials lead to more emissions invested in materials production, thus material efficiency becomes especially important.
iii) Risk of supply chain rupture is not necessarily driven by raw material use; it may appear indirectly from use of materials in supporting functions.
iv) Small parts may contribute largely, meaning that the environmental scores used for ecodesign must be made using a comprehensive scope.
v) Advanced manufacturing implies some particular properties, and this may lead to misleading conclusions when design decisions are based on existing ecodesign tools.
vi) Finally, ecodesign offers vital insights into the supply-chain of materials and manufacturing processes.

Full reports and data are available through the stakeholder website, **Ecodesign alliance for advanced technologies**[1]. The website hosts literature reviews, methodological reports, and environmental scores for an extensive list of materials, manufacturing processes and space propellants. Industry consultations and review procedures will follow in the fall of 2015.

1 INTRODUCTION

Life-cycle assessment (LCA) provides environmental information over the life of products. It supplies the indicators for environmental decision-making in the design process, and covers materials extraction, manufacturing, use and end-of-life treatment for product systems. Quantitative environmental scores, termed life cycle inventory (LCI), summarize the emissions and resource uses that appear from the system under study. The LCI datasets are used for impact evaluation, to compare overall risks to human health, ecosystem damages and resource depletion [2].

Technologies for space, aerospace or other demanding applications differ from the traditional large volume productions in many ways. They involve advanced materials, specialized manufacturing processes and smaller production volumes. Testing and functional requirements are also different when producing for space and aerospace. These factors have some significant implications for the LCA studies that are used to support ecodesign practices.

- Technologies for advanced applications are earlier in development.

Literature concerning their environmental properties is immature or non-existent. This presents a tough starting point for ecodesign, as little information is readily available.

- Extrapolating conventional ecodesign tools into high-end manufacturing may carry vital errors.

[1] Website: http://advancedtechnologies.asplanviak.no/

Novel technologies and specialized materials are to a little extent covered by existing data. An adaption of ecodesign to demanding applications require expanding the library of processes beyond large volume production, while also maintaining internal consistency.

- Demanding applications involve conventional manufacturing techniques, with certain additional properties.

This renders the typical ecodesign tool irrelevant. It is a significant challenge to ensure that information used in the ecodesign process is space relevant.

1.1 Motivation – goal and scope

The goal of the project is to provide the elements for effective ecodesign of space systems. The scope covers cradle-to-gate for the materials, components and processes listed in Table 1, i.e., inputs from raw material extraction to final product delivered out from factory gate. Propellants are not described here and will be treated later. This paper focuses on sub-components where material or production properties deviate from conventional large-scale production.

The impact scope is wide, covering the conventional aspects in life-cycle assessment, i.e., emission and resource-use related impacts connected with effects on ecosystem, human health and depletion of abiotic resources[2]. In this paper, we focus on a shortlist, based on the most relevant impacts for the product system evaluated. Additionally, we consider use of critical raw materials following the definition from the European Commission, and emissions of priority list substances as defined by the REACH Directive. Critical raw materials are defined as materials with high economic and significant supply risk. The latter being estimated via a compact indicator for accountability, political stability and absence of violence, government effectiveness, regulatory quality, and rule of law in the region of origin.

The ecodesign score are developed using life-cycle assessment (LCA) methodology, in the form of life cycle inventory (LCI) datasets. These LCI datasets compile emissions and resource uses, referred to as environmental interventions, as they appear up to the factory gate. The datasets are developed from a European perspective, assuming the ecoinvent v3.1 database with the default allocation as background[3]. While the European perspective implies adaptations concerning energy and other generic inputs to the production, emissions are still included independent of where they appear.

Full reports for the methodology and inventories described here are available for industry consultation at the stakeholder website[4]. The work is performed under contract to European Space Agency, by Asplan Viak (Norway), ISQ (Portugal) and Sintef Raufoss Manufacturing (Norway) [1].

1.2 Examples discussed in this paper

The work includes an extensive list of space materials and manufacturing processes, many of which are applicable to applications besides space. In this paper, we focus on a few of the cases trying to answer the question: what happens when we make ecodesign relevant for demanding applications?

[2] This covers greenhouse gas emissions, acidification, eutrophication, eco-toxicity, particulate matter, ozone depletion, photochemical oxidant formation (smog), human toxicity, ionizing radiation, water, fossil and mineral resource depletion, and energy consumption.
[3] This means that we assume allocation at the point of substitution, i.e., that material to waste treatment is modeled up to either replacing other products or ending as final waste.
[4] *Ecodesign alliance for advanced technologies:* http://advancedtechnologies.asplanviak.no/

Our examples look into specialty aluminium alloys, photovoltaics for space, thermoplastics not previously described in literature, and additive manufacturing. We also include tank production, as an example of conventional manufacturing for space. Finally, we try to extract the main lessons.

Table 1: Modules in the full study

Type	Modules
Common processes	• European average electricity and heat • Auxiliary materials: Tungsten carbide, carbon fiber, high-speed steel, sanding and polishing inputs.
Materials	• Billet and powder: Al 7XXX alloys, Al Li 2XXX alloys, additive manufacturing alloys TiAl6V4 & AlSi10Mg • Tungsten metal • Thermoplastics: polyether ether ketone (PEEK), polyether imide (PEI) and polyphenylene sulfide (PPS)
Machining	Machining for aluminium alloys, titanium alloys, stainless steels, Inconel steel: • Milling, drilling, laser cutting, electroforming, spark erosion • Heat treatment: annealing, hardening, solution treatment and stress relieving • Welding: tungsten inert gas (TIG), metal inert gas (MIG), submerged gas welding (SAW), friction steer welding • Rubber polishing
Inspections	Non-destructive inspections (NDI) processes, hereunder eddy current, dye penetrant, expulsion efficiency, external leak, negative pressure, pressure cycle, proof pressure, total design load, ultrasonic, vibration test, volumetric capacity and x-ray/radiographic
Tank production	Various tank designs made from TiAl6V4 and titanium material • Cylindrical tank, with/without carbon fiber over-wrap • Various elliptical and spherical tank sizes
Nozzle extension	• Vulcain 2 engine
Structural elements	• Aluminium honeycomb • Carbon fiber reinforced polymer • Glass fiber reinforced polymer • Sandwich panels
Additive manufacturing	The following additive techniques are modeled, based on relevance for space: • Directed energy deposition single/multi-production: TiAl6V4 • Direct metal laser sintering single/multi: TiAl6V4, AlSi10Mg, stainless steel and steel alloys 17-4 and 316L • Electron beam single/multi: TiAl6V4 • Selective laser melting with stainless steel powder: M3 linear single/multi, SLM250 single/multi
Electrical & electronics	• Electronic market compact and single components: amplifiers, comparators, converter, CMOS, diode, receiver, regulator, voltage reference, voltage regulators, sample and hold • Harness modules: wires, braids, jackets, wave-guards and flanges • Li-ion battery: battery cell and battery assembly
Photovoltaics	• Solar cell: Triple junction GaInP/GaAs with Ge wafer • Solar panel assembly • Ge wafer production steps, including Ge extraction

2 SPECIALTY ALUMINIUM ALLOYS

Aluminium is a vital element in our society and life cycle data is available for basic aluminium, primary as well as secondary metal. Demanding applications require specific material properties achieved by specialty alloys, therefore the aluminium used in space and aerospace applications differ from the conventional. Many of the alloying elements are scarcer than aluminium and titanium, with implications for energy use and emissions in extraction. The alloying elements may also dominate resource depletion aspects.

It is interesting to investigate how the environmental performance of alloys of aluminum and titanium vary depending on alloy composition. Inventory datasets are developed for several alloys, with focus on alloys in 7000-series and aluminium-lithium 2000 series.

The 7000 family consists of high strength alloys central to demanding applications like space and aerospace. Zinc is the major alloying element, and magnesium in smaller percentages. Alloys Al7050, Al7075 and Al7475 are considered particularly relevant. Al-lithium alloys is an area for current research. The largest use of an Al-Li-alloy has been the 2195 alloy used for the construction of a super lightweight tank [3]. Alloy 2095 is another alloy that has been used for cryogenic tanks. Although several Al-Li alloys offer space grade qualities, most of them are relatively similar in composition.

Table 2: Modelled alloy compositions, based on maximally allowed alloy content and aluminium as remainder, with alloy signature elements emphasized.

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Zr	Ag	Li	Ti	Al
7050	0.12	0.15	2.6	0.1	**2.6**	0.04	**6.7**	0.15	-	-	0.06	87.548
7075	0.4	0.5	2	0.3	**2.9**	0.28	**6.1**	-	-	-	0.2	87.31
7475	0.1	0.12	1.9	0.06	**2.6**	0.25	**6.2**	-	-	-	0.6	88.17
2090	0.1	0.12	3	-	0.25	-	-	0.15	-	**2.6**	-	93.78
2095	0.12	0.15	4.6	0.25	0.8	-	0.25	0.18	0.6	**1.5**	0.1	91.45
2099	-	-	2.7	0.3	0.3	-	0.7	0.09	-	**1.8**	-	94.11
2195	-	-	4	-	0.4	-	-	0.11	0.4	**1**	-	94.09
2199	-	-	2.6	0.3	0.2	-	0.6	0.09	-	**1.6**	-	94.61
2024	0.5	0.5	4.9	0.9	1.8	0.1	0.25	-	-	-	0.15	90.90

The system boundary in our evaluation includes raw mineral extraction and refining, cast-house billet production with homogenization and infrastructure.

Impact assessment of the alloy billet production shows some interesting patterns, and we shall try to point to a few of them.

- **We find a significant variation in the environmental impacts.**

Greenhouse gas emissions, quantified by kg CO2-equivalents (CO2e), range from 15-20 kg per kg billet depending on alloy composition. Greenhouse gas emissions are linked to energy use, which for most of the alloys is ruled by the aluminium content, except for alloy 2095 where significant contributions to energy-related emissions appear also from lithium and silver.

- **Alloying elements must be modeled for proper comparison between alloys**

This is apparent for toxicity and resource depletion. Alloying elements may contribute significantly to environmental risk even at low contents, exemplified by silver in alloy 2095. At a concentration 0.6 % in weight, silver still represents about 20 % of freshwater eutrophication emissions and more than half of emissions linked with increased risk cancer in humans. Silver is also close to 100 % of abiotic depletion impacts for this alloy.

- **Mineral resource depletion depends on alloying elements.**

Copper, manganese, silver, magnesium, and lithium, are all metals emphasized, via scarcity issues or increase in energy use in extraction due to depletion of high-grade ores. As has been noted by others, many metals are poorly covered by LCA information [4]. This poses a challenge for application of ecodesign to advanced applications. The same is apparent for titanium and titanium alloy TiAl6V4, where neither titanium nor vanadium were present in core databases and new LCIs had to be developed.

- **Metal depletion issues also arise indirectly.**

The European Commission has defined a list of critical raw materials, which includes rare earth elements. Tracking critical raw materials in the production of Al-Li alloy 2095 we find that it largely appears from use of permanent magnets made from neodymium – a rare earth element. Such magnets are a vital part of secondary metal production. Thus, risk of supply chain disruption for alloys for space and aerospace is not necessarily connected to alloying elements themselves, they may be more relevant for other inputs to alloy billet production.

As an illustration, we provide in Figure 1 a benchmark comparison of selected alloys for some of the impacts considered. The focus is on resource depletion impacts. Metal depletion (marginal $) is a representation of cost of marginal extraction, while abiotic depletion is a method based on depletion of global reserves. Critical raw materials (CRM) is evaluated for all CRMs in one, or only considering rare earth elements. Depletion of ultimate reserves emphasizes silver use, while evaluation of metal depletion by effect on marginal extraction shows contributions from silver, copper and manganese. Magnesium is the major contribution if we look at all critical raw materials, while for rare earth elements it is the use of neodymium in the refining of scrap metals. Notice the smaller variation in global warming emissions (CO_2e), freshwater eutrophication and particulate matter formation, as examples of impacts mainly related to energy use, where the aluminium is the major source. The other impacts show much larger variation, and the ranking is not uniform between impact methods.

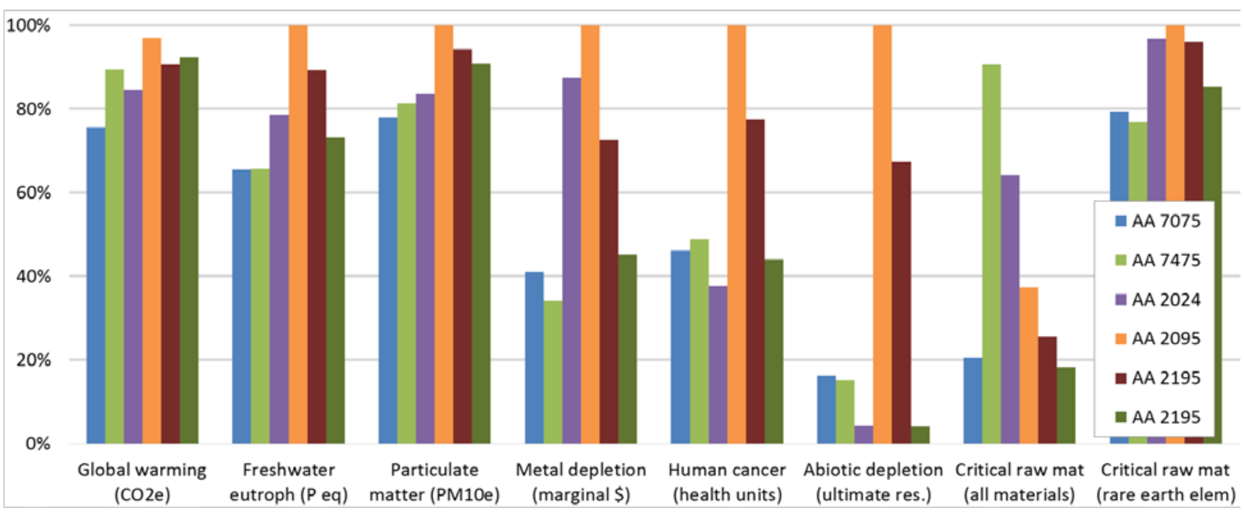

Figure 1: Environmental benchmark of selected alloys.

3 THERMOPLASTICS – NOVEL MATERIALS IN LCA

Thermoplastics have a long tradition in life-cycle assessment. Environmental scores have been published in several version, e.g., by Plastics Europe for conventional thermoplastics including polyethylene (PE), nylon, PET, polystyrene (PS) and polyvinyl chloride (PVC). However, space and aerospace make use of other materials, here polyether ether ketone (PEEK), polyether imide (PEI) and polyphenylene sulfide (PPS). This is a typical challenge when LCA and ecodesign is applied to a new context, that main elements are not described by existing data. Thus, ecodesign evaluation cannot be made without additional efforts.

Production of the selected thermoplastics is made by patented processes, and commercial interests make precursor data difficult to obtain. A first approximation is made from available literature, supported with theoretical estimations. Figure 4 compares the final inventories, with focus on impacts related to energy use and toxic risk from emissions in production. The figure includes global warming emissions (quantified as CO2-equivalents), use of fossil energy (in MJ), freshwater eco-toxicity and human health impact as modeled by the USETOX method. Energy use and greenhouse gas emissions for the new thermoplastics compare to previous estimates for the conventional thermoplasts. The main driver of production impacts for PPS, PEI and PEEK is related to precursors, which in our model is modeled with high degree of uncertainty. Energy use in production and use of infrastructure are of less importance.

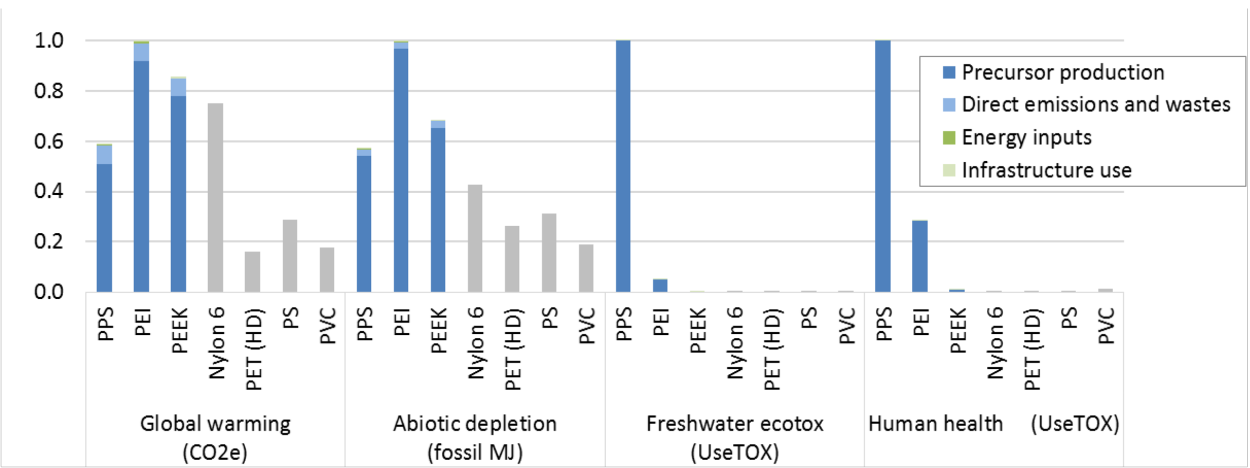

Figure 2: Environmental benchmark of modelled thermoplastics and literature thermoplasts.

Given the high uncertainty in inventories, results cannot support the statement that impacts from the space thermoplasts are higher than from the more conventional plastics. However, they do indicate that good representation of precursors is important for correct representation of their relative environmental scoring, in terms of their production upstream as well as the volumetric use of them in production of end thermoplastics. This should be particularly emphasized for comparison of health and eco-toxic impacts, where the impacts estimated here indicate significantly higher risks than for the more conventional thermoplastics.

4 PHOTO-VOLTAIC CELLS FOR SPACE

Si-based solar cells have been used for space applications earlier, but following the breakthrough in III-V-based multi-junction solar cells, Si technology has now nearly disappeared from space and multi-junction

cells have become standard since 2009 [5], [6]. The cost difference between technologies are however considerable, with a typical GaAs or Ge wafer costing about 100 times more than a Si wafer.
CdTe (cadmium telluride) and CIGS (copper indium gallium diselenide) are other thin-film technologies that are have previously been described in literature for space applications [7]–[9], but the development has since then gone in the direction of III-V-based multi-junction cells. We therefore select for analysis GaAs III-V multi-junction cells, mainly due to higher efficiencies of the technology [5], [10], and advantages in radiation-hardness, small temperature coefficients, high reliability, high voltage and low currents [6].

4.1 System for analysis

To conclude, the system set for analysis is triple junction solar cells of the type GaInP/GaAs on Ge wafer. Given differences in materials used, these are principally different from Si-based cells described in most prior studies. An relevant inventory for terrestrial GaInP/GaAs is described by Mohr et al. [11]. The Mohr study is largely complete, though some further developments are deemed necessary:

- Current technology uses a thinner Ge wafer, 150 µm instead of GaAs 350 µm assumed by Mohr.
- Germanium extraction and Ge wafer production is included in the scope.

Life cycle inventory datasets (LCI) are developed for the solar cells and solar panels complete with substructure, cables and connectors/busbars. The functional unit is defined as one unit of GaInP/GaAs/Ge solar panel with 150 µm Ge wafer and honeycomb substructure. The cell efficiency in the range of 28-30%. Solar panel dimensions are assumed according to the Alphabus solar array [12], specifications for solar panels provided by Pfefferkorn et al. [12] and product datasheets from relevant suppliers. The inventories are modelled as cradle-to-gate processes. [HB1]

4.2 Germanium mining – example of modeling extensions

Germanium is a by-product of zinc production. While zinc production is described the ecoinvent database, these do not include Ge extraction from nature or germanium as final product. Extensions are therefore made to the ecoinvent process, based on mass allocation for the mining operation using production volumes from US Geological Survey. By inspection, the assumptions compare with Ge production described elsewhere [13].

Preparation of the Ge wafer has been modelled based on information in literature [14], for same wafer 150 µm thickness and data from a major supplier of Ge wafers (Umicore). The following main steps are included for the production of Ge wafer: chlorination and hydrolysis, zone refining, supportive processes metal refining, czochralski Ge chrystal growth, wafer manufacturing, cleaning and inspection.

Germanium is listed by the European Commission as a critical raw material, and this is our motivation for specifically modeling germanium wafer production. This provides a better representation of the supply chain for generalized photovoltaics for space. Previous studies conducted under the auspice of the ESA indicated that germanium in PV systems contribute significantly to metal depletion aspects of space systems.

4.3 Results of the analysis

Based on the resulting inventory, the contribution to selected impacts is presented in Figure 2 for a photovoltaics panel assembly. The results indicate that main impacts are related to the solar cell, with significant contributions primarily from interconnectors and the aluminium honeycomb and carbon fiber reinforced polymer structure. Further detail for the production of the PV cell is provided in Figure 3.

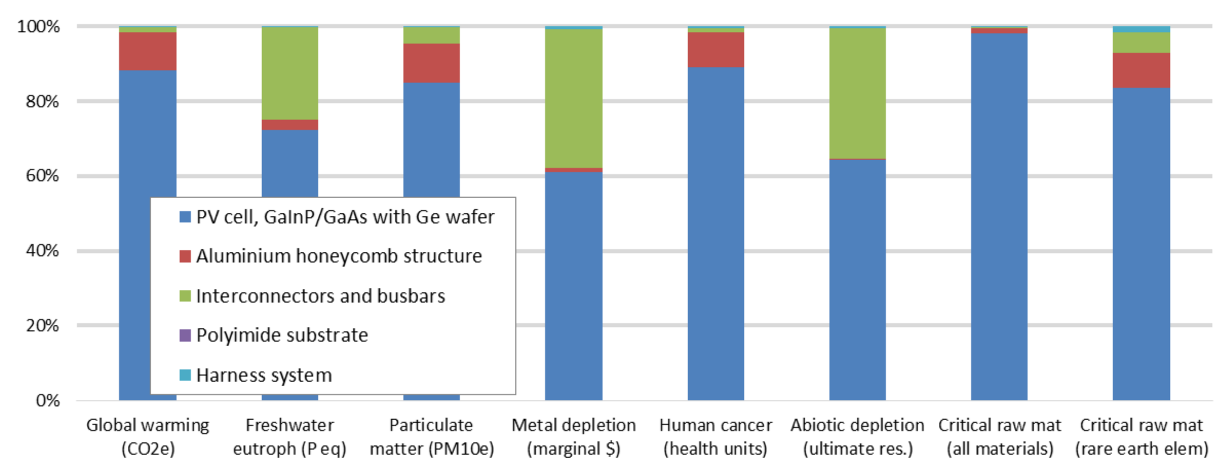

Figure 3: Contribution analysis for a PV solar panel assembly.

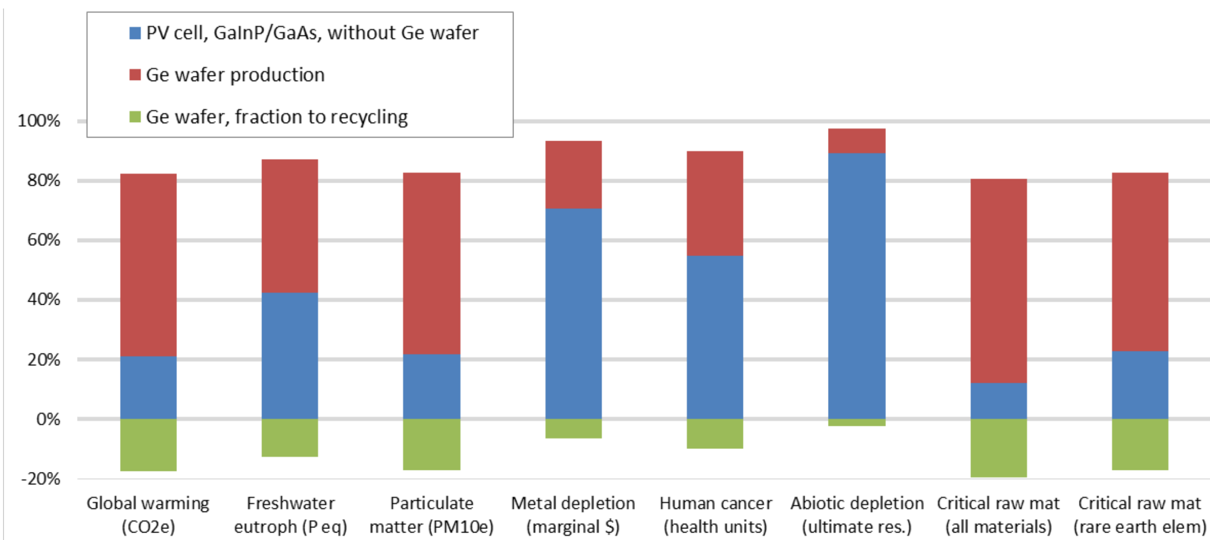

Figure 4: Contribution analysis for PV cell production

The full insight into the repercussion of environmental aspects through the production chain for PV systems is difficult to obtain via one single graphic. We shall therefore try to describe a few of the main mechanisms driving the environmental impacts.

- Gold and silver layers in PV system and interconnectors are most important for metal depletion impacts.
- Fluorspar, a substance listed as critical raw material by the European Commission, is assumed used in the production of Ge wafer and this is the major contribution to CRM. Considering only rare earth elements, we find the same as previously for aluminium billets that use or these is connected to scrap refining far upstream from the PV production.
- Global warming emissions, i.e., CO2-equivalents, is primarily due to energy use in solar cell and wafer production. The same is seen for particulate matter emissions and freshwater eutrophication, both typically connected to air emissions from energy generation.

- Health risks from release of toxic compounds with cancerous effects attached appear primarily from production of silver and gallium, both used in the solar cell.
- The harness and polyimide substrate seems to have little contribution to the overall environmental impacts.

5 UNDERSTANDING ADDITIVE MANUFACTURING

Additive manufacturing (AM) is a technology that offers great promise for the manufacturing industry. Several additive manufacturing techniques, popularly known as 3D printing, are available today. The possibility to offer rapid mobilization and complex parts are of particular interest to the space and aerospace industry. Additive manufacturing allows low waste and small production volumes at reasonable costs, and geometries beyond what is available from conventional manufacturing. Direct metal fabrication is highly relevant for demanding application with high levels of R&D and demand for rapid parts production and prototyping [15].
As promising as AM may be, little information is available to describe the environmental properties of additive manufacturing when it comes to energy use, material sourcing and efficiency [16]. To our knowledge, our study represent the first attempt at a comprehensive environmental assessment of additive manufacturing techniques.

In the full report are described life cycle inventories for several AM techniques; see list in Table 1. The following is included in our evaluation:

- Production of steels (17-4 PH, 316L), titanium (TiAl6V4) and aluminium (AlSi10Mg) alloys for additive manufacturing, including alloying elements as described previously in Chapter 2.
- Aluminium and titanium powder production by gas-atomization (most AMs), and wire drawing (for directed energy deposition).
- Energy and atmosphere gas consumption, based on data published by machine suppliers.
- Machine and infrastructure, estimated from expected lifetime and production volumes.

5.1 Direct metal laser sintering with titanium powder

An overall comparison of all additive manufacturing techniques is beyond the limits of this paper. As an illustration, we select direct metal laser sintering using titanium TiAl6V4 powder. A list of the inputs required per kg product from the process is provided in Table 3 below.

Direct metal laser sintering (DMLS) is a powder-bed fusion technique. It uses a laser to melt the powder layer-by-layer to create the requested product shape, using powders of aluminium, titanium or stainless steel. The dataset models the machine EOSINT M270, with given deposition thickness and nominal build volume. Processing is done under argon atmosphere, with the generator integrated into the machine.

Impact contribution is presented in Figure 5, for a selection of impacts. We include here global warming emissions, freshwater ecoxicity, health impacts and abiotic depletion indicators for use of mineral resources and fossils. Main contributions are from powder, argon gas and energy, and notably for the machinery and infrastructures used for the aspect of abiotic depletion. The latter finding is explained by the low production volumes from AM techniques, particularly when impacts are distributed per kg product for a lightweight material such as titanium. Interestingly, argon and energy use contribute on the scale of titanium metal production for impacts related to from release of potentially toxic substances. However, the quality of the data would benefit from empirical observations. Still, the results point to all inputs as potentially significant to the overall evaluation.

Through not shown here, similar findings are present also for the other additive techniques, implying that proper evaluation of AM requires that machinery and auxiliaries are included.

A further analysis of environmental impacts for titanium powder process shows that other inputs besides the titanium billet are important. Gas atomization is made under argon pressure, with potentially very high argon use. Argon recycling systems are available, and these have been included in the model. Thus, liquefaction and recycling of argon is achieved at the cost of quite high liquid nitrogen consumption in cooling of the outflow gas.

Table 3: Inventory for direct metal laser sintering with TiAl6V4, machine with multiple product functionality, per kg product made.

Materials/fuels			Source
Titanium powder, TiAl6V4 alloy, 25-45 µm	1	kg	Insignificant loss assumed
Argon, liquid	19.0	kg	Supplier: EOS
Metal working machine	0.714	kg	Own estimate
Metal working factory	2.0E-09	p	Own estimate
Electricity, medium voltage	78.6	kWh	Supplier: EOS
Auxiliary service inputs *			

* Use of waste treatment services, heating of buildings and water supply represented by a generalized proxy process, not listed here.

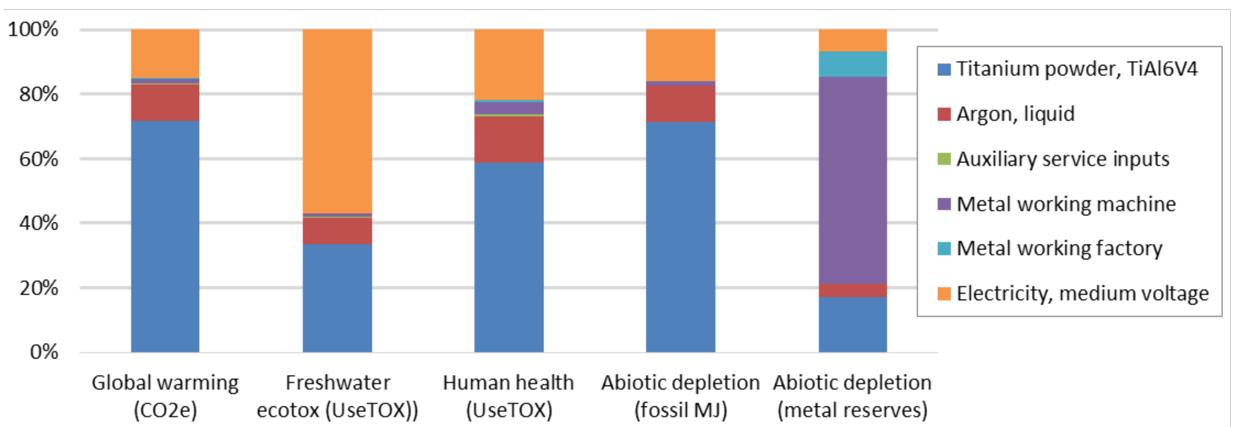

Figure 5: Contribution analysis for 1 kg production from direct metal laser sintering with TiAl6V4, machine with multiple product functionality.

6 TANK PRODUCTION – ADVANCED MANUFACTURING

Tank production for space is a production that utilizes several of the conventional manufacturing techniques included in our scope, and offers a useful reference to show the use of data to identify major challenges for manufacturing for space. Typical tank geometries are spherical and cylindrical with either hemispherical or Cassini shaped domes.

For the purpose of exemplification, we present here an environmental evaluation of cylindrical tank with carbon fiber over-wrap. The unit for analysis is one m3 of tank capacity, with contributions estimated from the following; see further descriptions elsewhere [1]:

- Production of primary titanium material,
- Machining by turning and milling, and tungsten inert gas (TIG) welding
- Heat treatment
- Carbon fiber over-wrap
- Degreasing
- Non-destructive inspections (NDI)

The NDI procedure includes a series of inspections such as volumetric capacity, proof pressure, pressure cycle, negative pressure, vibration test, total design loads, external leak, dye penetrant, x-ray, ultrasonic and automated eddy current inspection. The NDIs mainly add energy use to manufacturing processes.

Manufacturing processes cover energy, materials, auxiliaries, infrastructure and waste processes. Milling and turning are material removal processes, thus they provide material for recycling. Recycling frees material for reuse, which cause turning and milling to appear as having negative impacts. Our modeled tank of capacity 1m3 involves removing 93 % of a starting mass of 921 kg, to end with net tank titanium mass of 58 kg. Thus, the 863 kg titanium sent to recycling carries larger benefits than the energy involved in milling and turning processes.

Final impact contributions are presented in Figure 6, split between main processes.

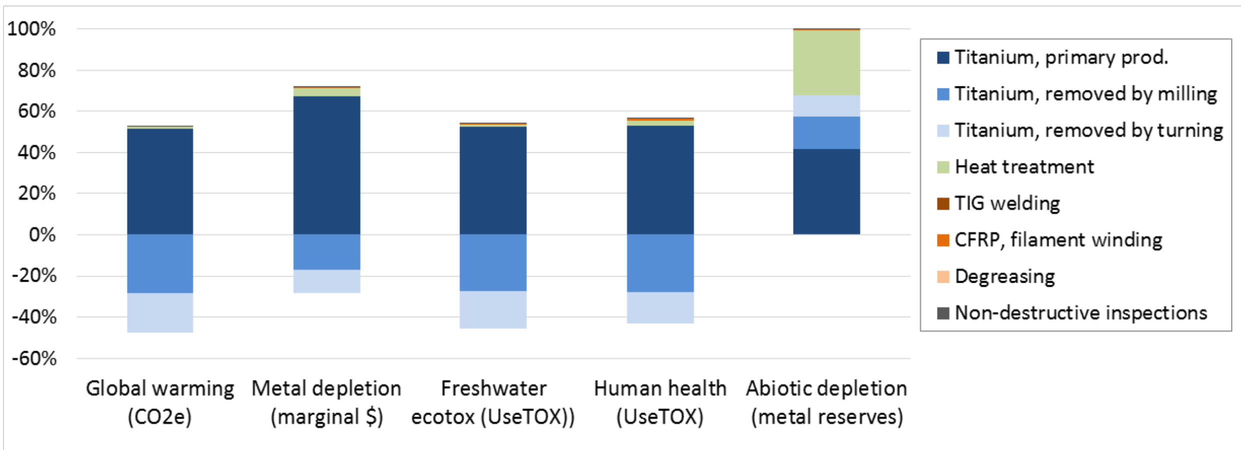

Figure 6: Contribution analysis for cryogenic tank production, cylindrical titanium tank with carbon fibre reinforced plastic overwrap.

Clearly, the dominant element for impacts is the titanium efficiency, from primary production and benefits by material recovery of titanium removed by turning and milling. This mechanism applies to all impacts except abiotic depletion of mineral reserves, seen in the right-most column) of Figure 6. Metal depletion is handled by two impact methods: metal depletion (marginal cost method) and depletion of ultimate reserves (abiotic depletion – metal reserves). The latter method prioritizes ferro-metals, while the first prioritizes titanium. Thus, with the perspective of ultimate reserves, iron and steel used in infrastructure for machining and heat treatment dominate over primary titanium production.

The main message is that material efficiency and effective recovery is a major challenge for tank production, more so than supporting structures, process inputs and energy used in production.

7 INSIGHTS

Results indicate that advanced manufacturing carry particular properties when compared to the conventional, which may lead to misleading conclusions when design decisions are based on existing ecodesign tools. Efforts to adapt ecodesign tools for demanding applications will require significant effort, yet is recommended.

To answer the question at the beginning of the paper, when ecodesign is made relevant for demanding applications we find that it offers a vital insight into the supply-chain of materials and manufacturing processes. The findings are valuable information for R&D and strategy within the space and aerospace industry.

We have described some examples from developing the basis for ecodesign for space systems, as a representative case of demanding applications. The examples allow some central conclusions to be drawn.

- **Materials for demanding applications are not covered by current tools.**

Regarding metal alloys, the results show the need to include all elements for proper evaluation, especially for metal depletion aspects. Small contributions may lead to largely different environmental weights. Similarly, thermoplastics for space show tendencies to differ from conventional thermoplasts for energy-related impacts, and the potential for vastly larger toxicity scores. Findings should be supported by better data and we welcome stakeholder responses to better the modelling.

- **Specialized materials lead to more emissions invested in materials production.**

Material efficiency therefore becomes especially important for demanding applications. We are uncertain about recycling procedures at industrials, but recommend a strong focus on closed recycling loops and maintaining material properties through the recycling process. This is underlined by the case shown for tank production.

- **Risk of supply chain rupture is not necessarily driven by raw material use.**

Dependencies of critical raw material use may occur also indirectly from use of materials in supporting functions. Examples described in this paper include fluorspar used in production of germanium (Ge) wafer, and neodymium in magnets utilized in metal supply chains.

- **Small parts may contribute largely**

Silver, gold, gallium, and germanium are metals used in photovoltaics for space. The first two are mainly parts of the electronic system, while Ga and Ge are core parts of the solar cell itself. Wafer production is a major contributor to the environmental performance of the photovoltaic system, as are gold and silver in electronics. Gold and silver use is not typically part of the technical descriptions for solar cells and estimates are highly uncertain. Still, small masses may contribute large parts of the environmental performance. Similar findings are made for tungsten in other electronic components for space.

The need for a comprehensive scope is underlined also for additive manufacturing. Proper evaluation of AM requires that the analysis goes beyond material and energy, to covers also machinery and auxiliaries. Additive manufacturing is a small volume technique, implying much larger contributions from infrastructure. Infrastructure use is gaining more attention also in life cycle assessment of conventional manufacturing, even if it rarely shows significant impacts. The machine use presented in this paper for direct metal laser sintering show vastly larger machine use than for conventional manufacturing.

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