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Developing a Parameterized Embodied Emissions Calculator for telecommunication networks equipment (PEEC)

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Abstract

Temperature on the surface of the earth has already increased by 1°C above pre-industrial levels. To have a chance to keep global warming under 1,5°C, greenhouse gas emissions from human activities should be halved by 2030, reaching net zero in 2050. Every business sector is concerned. Although the Information and Communication Technology (ICT) sector can be part of the solution by enabling the emergence of more sustainable practices, it remains an industry with a considerable footprint.

The work in this thesis helps to estimate a part of this footprint. We developed PEEC, a Parameterized Embodied Emission Calculator, allowing to assess the greenhouse gas emissions due to telecommunication network equipment. PEEC counts the cradle-to-gate emissions, i.e. the emissions of all activities happening before the use of the product (mining and transformation of raw material, production of components, assembly, packaging, transport, and support operations). It is a flexible and user-friendly MS Excel worksheet, intended for users with different level of knowledge on the product. PEEC could assist mobile operators to report their scope 3 emissions, support research projects, and help answering questions related to embodied footprint of telecom network products in the industry. At this stage, the tool has been trialed at an older Ericsson base station and conditions from 2014. This showcased the functioning of the tool and estimated the embodied carbon emissions of the assessed base station at 4,4 tons CO_2eq, consisting of 1,8 tons in the raw material phase, 1,6 tons in the production phase, 0,7 tons during the transport along the supply chain and 0,4 tons for Ericsson's own activities. Detailed conditions behind these numbers are provided in this report.

Prior to the implementation, user expectations on such a tool have been collected and used to build the requirements. Usability have also been taken into account through workshops and discussions with stakeholders. Throughout the project, we tried to balance the trade-off between the scientific rigor of Life Cycle Assessment (LCA) and the needs of the industry. Previous LCA models and established standards in the field have provided the foundation of the embodied emission model, transparently described in this report.

LCAs of complex products such as ICT hardware with dynamic and global supply chains have high uncertainties. The results given by a simplified LCA tool like PEEC have even higher ones. The sensitivity analysis reveals a large dependance of the results for embodied emissions on material emission factors such as aluminum or gold, and production emission factors such as the manufacturing of integrated circuits. In general, the user should be careful with the assumptions used and always co-present the results with details regarding assumptions, boundaries and data sources as well as a disclaimer.

Sammanfattning

Jordens globala temperatur har redan ökat med 1°C jämfört med förindustriell tid. För att undvika en global uppvärmning över 1,5°C, behöver växthusgasutsläpp från mänskliga aktiviteter halveras senast till år 2030 och nå netto noll år 2050. Samtliga sektorer har ett ansvar att minska sina utsläpp. Även om informations- och kommunikationsteknikseKtorn (IKT) kan utgöra en del av lösningen genom att möjliggöra utvecklingen av mer hållbara praktiker, förblir sektorn en industri med ett betydande miljöpåverkan.

Det här examensarbetet bidrar till att kunna estimera en del av detta avtryck. Vi skapade PEEC, en parametermodell för de utsläpp som kan kopplas till en produkt redan innan den tas i drift (*eng.* embodied emissions) som gör det möjligt att uppskatta sådana växthusgasutsläpp från utrustning avsedd för telekommunikationsnät. PEEC beräknar alltså samtliga s k vaggan-till-grinden utsläpp: utsläpp från alla aktiviteter som sker innan användning av produkten (såsom utvinning och omvandling av råvaror, produktion av komponenter, montering, förpackning och transport). Verktyget PEEC är ett flexibelt och användarvänligt kalkylblad i MS Excel, avsett för användare med olika kunskapsnivåer om telekom-produkter. PEEC kan hjälpa mobiloperatörer att rapportera sina Scope 3-utsläpp, stödja forskningsprojekt och besvara frågor relaterade till vaggan-till-grinden utsläpp för telekomnätprodukter. I detta skede har verktyget testats på en äldre Ericsson-basstation och med data gällande år 2014. Detta test visade att verktyget fungerar och skattade vaggan-till-grinden utsläppen från den bedömda basstationen till 4,4 ton CO2-ekvivalenter. De skattade utsläppen bestod av 1,8 ton från råvaruutvinning, 1,6 ton från produktion, 0,7 ton från transporter längs försörjningskedjan och 0,4 ton från Ericssons egen verksamhet. Beräkningar för dessa siffror finns detaljerade i denna rapport.

Före implementeringen av verktyget har användarnas förväntningar undersökts och använts till att specificera krav på verktyget. Användbarheten har betraktats genom workshops och diskussioner med intressenter. Under hela projektet gjordes en avvägning mellan de höga kraven på en vetenskapligt korrekt livscykelanalys (LCA) och branschens behov. Tidigare LCA-modeller och etablerade standarder inom IKT-branschen har legat till grund för den använda modellen för vaggan-till-grinden utsläpp, vilken beskrivs vidare i denna rapport.

Livscykelanalyser för komplexa produkter såsom IKT-hårdvara med dynamiska och globala leveranskedjor har en hög osäkerhet. Osäkerheten hos resultaten från ett förenklat LCA-verktyg som PEEC blir därmed ännu högre. Känslighetsanalys har därför genomförts och visar att storleken på vaggan-till-grinden utsläppen starkt kan kopplas till materialemissionsfaktorer för metaller såsom aluminium eller guld, och produktionsemissionsfaktorer såsom tillverkning av integrerade kretsar. I allmänhet bör användaren vara försiktig med vilka antaganden som görs samt vara noga med att alltid presentera resultaten tillsammans med detaljer angående gjorda antaganden, avgränsningar och informationskällor samt en varning om att resultaten bara gäller för de förutsättningar som anges.

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Table of contents

List of abbreviations

DU	Digital Unit
IC	Integrated Circuits
ICT	Information and Communication Technology
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
PAIA	Product Attribute to Impact Algorithm
PDU	Power Distribution Unit
PEEC	Parameterized Embodied Emission Calculator
PSU	Power Supply Unit
PWB	Printed Wiring Board
RAN	Radio Access Network
RBS	Radio Base Station
RRU	Remote Radio Unit
RU	Radio Unit

1 Introduction

1.1 Context

Climate change is one of the biggest challenges humanity has to face in the 21st century. According to the Intergovernmental Panel on Climate Change (IPCC), human activities have already caused an increase of the average global temperature by 1°C above pre-industrial levels [1]. This already has tangible consequences on the world's ecosystems and human populations. In order to limit global warming below 1.5°C, global net anthropogenic CO_2 emissions should decline by about 45% from 2010 levels by 2030, reaching net zero emissions by 2050 [1].

New technologies have a great potential to be part of the solution by helping to decarbonize the economy. However, it should not be forgotten that they are also part of the problem. Behind the seemingly dematerialized world that they seek to create lies the production of hardware, the maintenance and operation of data centers and networks, and the management of electronic waste. A very recent study [2] (preprint) estimates the Information and Communication Technology (ICT) sector to be responsible of 1,8-2,8% of global greenhouse gas emissions, and sees this ratio as likely to increase. At the same time ITU, GSMA, GESI and SBTI puts forward trajectories which outlines opportunities for the sector to halve its emissions by 2030. Awareness and concern are also existing in the public sphere, at a time when countries and operators are racing to roll out the 5th generation (5G) of mobile network. In France, some sixty elected officials signed an editorial in September 2020 to ask the government for a debate on 5G's usefulness and impact on the climate [3].

Corporate responsibility. Faced with these observations, many companies in the ICT sector have made ambitious commitments to become sustainable. Ericsson outlines for example an opportunity to roll out 5G without increasing the overall ICT footprint [4]. Some have joined the Science Based Targets initiative [5], a concerted effort to fulfill the abovementioned IPCC emission reduction path. This involves innovation in sustainable technologies, but also clear reporting and reduction of the companies' own footprints. Companies' emissions are generally divided into three "scopes" (GHG Protocol, [6]): direct emissions from owned or controlled sources (scope 1), indirect emissions from the generation of purchased energy consumed (scope 2) and all other indirect emissions that occur in the company's value chain (scope 3). Taking the example of a factory, emissions from a fossil-fuel powered machine would be reported as scope 1 whereas an electric machine has indirect emissions reported as scope 2. Production and transport of purchased goods, research and development or employees commuting would be all counted in the scope 3. To comply with the GHG protocol, companies should report their scope 1 and 2 emissions, but an increasing number of them also report on scope 3.

Scope 3 reporting. Included in scope 3 are the goods and services purchased by the company from its suppliers as well as downstream activities like the processing, use and end-of-life of the sold product. This way, a mobile operator buying a base station from a telecom equipment provider would report the emissions linked to the *production* of this base station in its scope 3. For its part, the telecom equipment provider would report as scope 3 the *operation* (maintenance, electricity use) of the sold base station. Scope 3 reporting is standardized by GHG Protocol [7] and a sector specific guidance for ICT companies is provided [8]. The scope 3 concept frames these emissions from an organizational perspective, but the same emissions could also be investigated from a product perspective using Life Cycle Assessment (LCA) based methodologies to derive the carbon footprint of a product.

Product carbon footprint. At this point, several ICT companies are starting to provide carbon footprint of their products with details on their methodologies. For instance, Dell releases a carbon footprint for each and every product in its portfolio on its website [9] and Apple claims that 45% of its scope 3 annual reporting [10] is backed up by standard-compliant LCA studies like its "Product Environmental Reports" [11].

Embodied emissions. In this report, "embodied emission", "embodied carbon footprint" or "cradle-to-gate emissions" of a product designate all related greenhouse gas emissions occurring before its usage. These include the emissions related to the product development, mining of materials, manufacturing, transport, sale etc. all the way to the customers' warehouses.

1.2 Problem

This master's thesis has been carried in collaboration with the Swedish telecom equipment provider Ericsson which has been performing research in the area of environmental studies of ICT applications since 1994. In the field, various problems have been identified:

- Relatively few peer-reviewed assessments have been done for ICT equipment and there is not yet a consensus on the overall footprint of the sector (see the recent review [2]).
- Yet, as climate reporting practices evolve, an increasing number of customers turn to Ericsson to ask about the carbon footprint of the products it sells.
- Carrying fully standard-compliant studies is time consuming and challenging given that current legislation does not require suppliers to provide environmental data.
- To the best of our knowledge, there is no model publicly available for environmental assessment of mobile network products.

Consequently, up to now, Ericsson was providing its customers with rough estimations of the products' embodied carbon footprints as a ratio of their power consumption derived from their studies of the sectorial carbon footprint. This estimate was motivated by the condition that most carbon emissions of network equipment are associated with the use stage (embodied emissions represent typically less than 20% of the use phase emissions).

1.3 Research question

Hence, the research question addressed in this thesis is:

- How could embodied emissions of telecommunication networks be estimated in a streamlined way?

We focused on the idea of building a parametric model, i.e. a tool estimating embodied emissions based on some parameters given as input. The research question was then divided into sub-questions that constituted the milestones of the project:

- What are the expectations on a parametric model for embodied emissions from intended users (Ericsson stakeholders)?

- Are there any relevant parametric models for ICT proposed in academic and other literature? Have they been validated and/or evaluated? If so, how?
- How could models from the literature, Ericsson´s data from earlier studies and/or other data sets be adapted into a parametric model for telecommunication networks (and in particular for Ericsson's products)?
- How valid is the resulting parametric model?
- How could it be used to support operators and other stakeholders assessing their organizational and product-related footprints?

1.4 Outline

This report is composed as follows.

The Background provides the reader with useful information on life cycle assessment and a literature review on parametric models for ICT products.

Further, we describe in the Methods how user expectations were considered and how the parametric model was built.

The Results chapter presents PEEC (Parameterized Embodied Emission Calculator), the outcome of this thesis. The tool itself is described, as well as the underlying model, an example of its application and how it could be useful for Ericsson stakeholders.

Finally, we debate the validity of the model and the limitations of this thesis in the Discussion before providing Future work perspectives and a Conclusion.

2 Background

A first step of this thesis was to become familiar with the notion of Life Cycle Assessment (LCA) and its use for environmental assessment of ICT devices. We then looked for parametric models for embodied emissions in the literature, principally through advices and snowballing. This section presents the main learnings from the literature review.

2.1 Life cycle assessment (LCA)

LCA is the most comprehensive and widely recognized method to assess the environmental impacts of a product or service.

2.1.1 General description of the method

When conducting an LCA, the entire life cycle is taken into account, from raw material extraction to end-of-life, including production, transport and use stages. Different impact categories (e.g. Global Warming, Human Toxicity, Resource Depletion, Acidification, …) are reported upon to capture environmental harm in the most accurate way possible. LCA's rigorous methodology is standardized by the International Organization for Standardization (ISO) in ISO 14040 and 14044 [12], [13]. It consists of four phases:

1. **Goal and scope definition**. The intended outcomes of the study and system boundaries are defined.
2. **Life Cycle Inventory analysis** (LCI). Data collection on every environmentally relevant flow associated with the object of the study throughout its life cycle. An elementary flow can be the mining of a specific raw material as well as the usage of the assessed product.
3. **Life Cycle Impact Assessment** (LCIA). Impact categories and indicators are chosen.
4. **Interpretation and results**. Conclusions and reporting of the results.

2.1.2 LCA for ICT

In addition to the ISO previously cited, different supportive documents have been released in the last decade to provide standards and methodology guidance for LCA in the ICT sector: the joint international standard from ITU/ETSI [14], [15] which supplements the aforementioned ISO standards, the scope 3 reporting guidance from Greenhouse Gas Protocol [16] which outlines the organizational value chain footprint, and the emission accounting guidance from IEC [17]. Full compliance with these documents is hard to reach because of the complexity of ICT products and supply chains and the data collection efforts that this entails.

Despite this, a rather recent literature review [18] identifies around 70 studies between 1995 and 2015 carrying out a detailed LCA on ICT products. According to this review, the products that have attracted the most attention from research are desktops and notebooks, followed by mobile phones. Data collection efforts are alleviated in about two thirds of the cases through the use of secondary data. The rest of the studies include primary data such as manufacture or disassembly data, surveys or interviews. Another review of the field [19] also identifies personal computers as the most addressed ICT devices in the literature. Unsurprisingly, the production and use phases are detected as the most impactful life cycle phases. The use phase is dominant for most products while the production phase dominates only for small devices with short life spans. Every time, integrated circuits and printed circuit boards are the most significant contributors to the overall environmental impacts. Overall, few studies are found on telecommunication networks.

2.1.3 Limits of LCA

The LCA for ICT standard [14] acknowledges that collecting enough data to measure the absolute environmental performance of a product is beyond reach. LCA should be used to understand the relative importance of the different life cycle stages and elementary flows and results should only be interpreted based on their associated assumptions.

Even if LCA is widely recognized as a trustful method for environmental assessment, many drawbacks are cited by practitioners. Firstly, this is a time-consuming and expensive method due to intricate data collection often out of reach. Moreover and despite the various standards, results from different studies are difficult to compare because they do not have the same boundaries, assumptions or data sources [19]. Results should always be accompanied by a disclaimer reminding that comparisons between studies are not possible unless contextualized according to [14]. In addition to this, there are large uncertainties associated with LCA results arising from statistical uncertainties of data, scenario choices (e.g. life time of a product, emission allocation for transport of one product) or insufficient knowledge on the studied system [14]. A collection of interviews with industry experts [20] concludes that assessed companies are generally aware of LCA but do not use it because it is hard to apply. According to the study, usable indicators for the industry would need to be easy to compute or even automated.

For all these reasons, simplified LCA methods have been proposed, attempting to address the trade-off between time spent and quality of the results.

2.2 Simplified LCA

The first thing that comes in mind to accelerate LCA is the use of specific software like GaBi or SimaPro. These tools are almost always used by practitioners as they guide the practitioner through the process and facilitate the use of secondary data thanks to large impact databases. The objective remains to perform a full LCA as defined by the standards and some burdens cannot be avoided.

Moberg et al. discuss possible LCA simplifications for ICT products [21]. They try on a reference LCA to exclude environmental impact categories, to exclude life cycle stages or to use secondary data. They conclude unsurprisingly that all simplifications lead to a loss of information. In particular, all impact categories are needed as they are indicators on different environmental issues and no category is representative of the others. However, they could prioritize the data collection efforts for future similar LCA to mitigate the uncertainties linked to the use of secondary data.

For carbon emissions only, several simplified methods and their limitations are proposed in the guidance for scope 3 reporting in the ICT sector [16]. One can for example use macroeconomic data as a proxy for carbon footprint. It is the case of the **Environmentally Extended Input-Output** (EEIO) method which uses input-output tables listing energy and material flows in the targeted industry sectors to provide high-level greenhouse gas emission estimates. Another simplified method is **life cycle stage ratio profiling** which consists of using historical LCA results on similar products to estimate the impact of one life cycle stage (e.g. raw material extraction, manufacture) as a ratio of another (e.g. use stage). This method has been used by Ericsson to provide the customers with estimations on embodied emissions of products (for example between 10 and 15% of use-stage emissions for a base station). The two previous methods require recent secondary data that do not (yet) always exist and they can mask trend shifts in the results. Always in the guidance [16] and closer to our work are the **hardware parametrization** and **component characterization** methods, aiming at developing relationships between product characteristics and impact categories. They require more detailed knowledge on the products but deliver more specific results.

Different methods are often used together leading to hybrid LCA approaches. For example, Vasan et al. present a combination of process-based LCA and the EEIO method [22]. More originally, Sousa et al. study the use of artificial neural networks for approximate LCA [23]. Some have also suggested the use of other environmental indicators to save the burden of LCA in companies (for an example, see the Key Environmental Performance Indicators (KEPIs) [24]).

2.3 Parametric models for LCA

LCA requires a lot of resources. Too simplified methods, on the other hand, might give misleading results. Identifying the most influent parameters and modelling their relation to the environmental footprint appear like an interesting method of tunable accuracy. In this section, we analyze parametric models for environmental assessment found in the literature. Focus is put on parametric models for carbon footprint and for ICT products. For each model we ask the following questions: what is the scope and purpose of the model? How were the parameters selected? How was the model validated?

Many parametric models for carbon emissions can be found in the literature, ranging from company- and industry-specific tools (e.g. [25]) to large-scale automated tools (e.g. [26]). Ostad-Ahmad-Ghorabi and Collado-Ruiz present a parametric model to estimate at early design stage the carbon footprint of a crane over its full life cycle [27]. Parameters are selected based on expert knowledge and the model is validated by comparing the results with LCAs. Niero et al. run a non-linear regression to identify two parameters that best predict the environmental impact of wooden pallets manufacture [28]. Huang et al. also use regression to conceive a simple model for the semi-conductor industry, only based on three product characteristics [29]. They use large process datasets from wafer manufactures.

To the best of our knowledge, only a few parametric models have been developed for ICT devices. Teehan and Kandlikar establish relations between the mass of different components and the embodied emissions associated with ICT products [30]. Their models are fitted with LCA results from the literature covering different ICT devices (tablet, laptop, server…). They also perform cross-validations which lead them to keep simpler models (more complex models tend to be overfitted). They, however, acknowledge the weakness of their very general model that tends to underestimate the carbon footprint of small devices and needs to be retuned as technology evolves.

A project similar to ours is PAIA[1] (Product Attribute to Impact Algorithm). It is a web-based tool allowing the user to estimate the carbon footprint of an ICT product (currently under scope: servers, network switches, storage arrays, desktops, notebooks, thin clients, all-in-ones, tablets and displays) by filling in its principal characteristics. Their sufficiency approach

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[1] Jointly developed by the MIT (msl.mit.edu/projects/paia/main.html) and the consulting company Quantis (quantis-intl.com/paia-a-sector-driven-tool-to-drive-transformation-in-ict/), PAIA is available for members of the project. Information can be obtained through the webpages, a webinar [31] and research papers, in particular [32].

is well formulated [32]: ”The hypothesis behind reaching sufficiency is that with each additional piece of information there is a decreasing marginal rate of improvement in model fidelity and a non-declining marginal cost of collection, such that eventually the decrease in uncertainty is not worth the effort to gather additional information.” For this reason, PAIA asks information about the product to the user in a priority order until the targeted model resolution is reached. Each product category has gone through a thorough analysis to prioritize the parameters according to their contribution to the overall carbon footprint and uncertainties associated with it. The tool, being not publicly available and not developed for telecommunication equipment, could not be used in this master’s thesis. Interestingly PAIA applies parametric model to equipment with a high percentage of their life cycle associated with the embodied emissions, while this project is focusing on network equipment where embodied emissions typically represents just a small fraction, implying a different sufficiency balance towards lower accuracy demands.

Another industry-oriented tool is Eco-Impact Estimator [33][2]. The product is divided into components where the carbon footprint contribution is modelled. As PAIA, the user is asked to fill in specific characteristics of the product and the results are displayed. A 15% margin of error compared to a LCA is claimed by the authors [34]. Current development of the tool focuses on including other impact indicators (namely resource depletion and water use) and updating the data. Here again, we could not acquire the precise assumptions and data sources.

Methods and main characteristics of the reviewed models are summarized in Table 1. The key learnings in the context of this thesis are:

- Regression or correlation analysis are strong methods to identify impactful parameters, but they need access to enough environmental data, which is not available in our case.
- Same problem applies for validation of the model.
- PAIA and Eco Impact Estimator are rather advanced tools that benefit from many years of improvement, but they are not public or transparent enough to be used directly.
- The parametric model for cranes [27] was developed in a situation similar to ours. We took inspiration from their methods.

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[2] Eco-Impact Estimator is developed by and for members of iNEMI consortium. Information can be obtained through the resources available in the project webpage (community.inemi.org/eco-impact_3).

Table 1: **Parametric models from the literature**

Ref.	Description	Purpose	Method	Parameters
[27]	Parametric carbon footprint model for cranes	Carbon footprint; Full life cycle; Early design stage; Product comparison	Choice of parameters based on expert opinion and full LCA conducted. Validation by running the tool on 6 new products and comparing the results with more detailed assessment.	Input = 13 primary parameters + optional secondary parameters; Output = carbon footprint distribution over the life cycles + home-maid environmental parameters
[28]	Parametric life cycle inventory for wooden pallets	Five impact categories; Improve design of future pallets	Exhaustively listing all the process units during life cycle and keeping all the parameters. Non-linear regression with 12 points to identify the most impactful parameters.	Input = 2 most impactful parameters; Output = 5 impact categories
[29]	Parametric model for embodied emissions of Integrated Circuits	Carbon footprint; Embodied emissions; Simplified estimation	Precise carbon footprinting of 7114 products through factory data. Correlation analysis to identify 3 key parameters then regression.	Input = 3 key parameters Output = carbon footprint of the product
[30]	Parametric model for embodied emissions of ICT products	Carbon footprint; Embodied emissions; Product comparison	Two datasets: LCAs with eco-invent or adapted from the literature (14 products) and dataset from Apple (22 products) Model fitting, test of different set of parameters and cross-validation.	Input model 1 = product mass and volume Input model 2 = 6 mass parameters Output = embodied emissions
PAIA[1]	Parametric carbon footprint model for ICT products	Carbon footprint; Full life cycle; Uncertainty calculation; Product comparison	Data collection for product families with associated probability distribution of uncertainties. The user iteratively enters parameters until the desired model resolution (calculated through Monte Carlo simulations) is reached.	Inputs = product characteristics Output = carbon footprint distribution over the life cycles + quantified uncertainty of the result
Eco Impact Estimator[2]	Parametric carbon footprint model for ICT products	Carbon footprint; Full life cycle; LCA estimations	Component characterization method. No detail on data sources or validation process are given.	Inputs = product characteristics Output = carbon footprint distribution over the life cycles + statistics

3 Methods

The previous chapter touched upon the barriers to adoption of LCA in the industry. They are mainly resource and competence challenges because such studies are time-consuming, need specific expertise and access to detailed information on the studied system which may be hard to acquire or may be lacking entirely. Besides, new products in the ICT industry are released to the market all the time and supply chains evolve quickly, which limits the understanding of environmental data and their evolution. How to build a carbon footprint tool for such a dynamic industry? This chapter presents the methods used in this work to answer our research question.

3.1 Identifying user expectations on a parametric model

As a first step towards the development of the parametric model, one objective was to understand the expectations on such a model from stakeholders in order to make it as useful as possible.

Discussions and workshops have been carried with the Ericsson Sustainability Research team to align on a common vision. They allowed us to build the requirements upon a strong experience in environmental assessment. Other stakeholders inside the company likely to benefit from the tool were sometimes involved in the discussions.

At the same time, customer requests were collected with the help of the sustainability team. 11 requests from 2017 to 2020 were gathered: two from research institutes and nine from mobile operators around the world. They are of different type: most of them are "requests for information" for company greenhouse gas emission scope 3 reporting, but others are open discussions about embodied emissions or requests for data for research projects. These inputs are briefly analyzed in Section 4.1, helping us defining the purpose of the tool.

3.2 Building the parametric model

Along the development of PEEC, all our decisions were taken according to one principle: **balancing the trade-off between the scientific rigor of LCA and usability in practice**. Whatever our decisions, we strived for transparency about how the resulting balance is achieved.

We took inspiration from similar work in the literature, presented in the Background (Section 2.3). The conclusions are that the method to build a carbon footprint model depends on its purpose (early stage estimates, automatic calculations, external communication, …), the data at disposal and the aimed scientific contribution. We investigated the methods and data used in the two similar tools available to the best of our knowledge: PAIA [35] and Eco-Impact Indicator [36]. A special interest has also been taken in the parameter carbon footprint model for cranes [27] as they have an angle close to ours (access to company-specific data).

In addition to the literature review, PEEC is anchored in a diversity of inputs:

- The recommendations from the joint LCA standard by ITU/ETSI [14], [15] (see the Discussion, Section 5.1.4)
- Two previous master's theses carried at Ericsson Sustainability Research: the LCA of a smartphone [37] and the LCA of core network [38]
- Customer requests (see Section 3.1 above)

- Input from an LCA expert
- Unpublished LCA studies, models and associated data

PEEC is described in Section 4.1 of the Results.

3.3 Experimental validation

The difficulty when developing a model for environmental assessment is that there is no actual measurement to compare the model against. It is impossible to isolate the system under study and put sensors in output to measure greenhouse gas emissions. One could at best compare the model's estimates to full LCA results, that are the closest we have to accurate accounting of all environmental burdens. But very few LCA have been performed for network equipment. Moreover, ensuring that the system boundaries are the same and achieving statistical significance is simply out of reach. In the future, one could compare the results of the model extended to the whole industry with a top-down approach from industry reporting data. This could be done later with more mature versions of PEEC.

In this work, our method to discuss the validity of the model is limited to the following four points, common in the field:

- **Main source of uncertainties.** Modelling assumptions and data uncertainties are screened and discussed.
- **Sensitivity analysis.** The sensitivity on the results of certain assumptions or key data is tested.
- **Comparison with related works**.
- **Compliance with standards.** Modelling assumptions and data collection methods are checked against the recommendation of the LCA for ICT standards [14], [15].

The experimental validation is performed in Section 5.1.

3.4 Improving the usability of the parametric model

As mentioned before, the intention in this project is to make a tool that practically helps the industry to report and think about its carbon emissions. For this reason, a lot of effort have been put into improving the user experience of PEEC. Most decisions in this regard were based on personal opinion.

In order to test the tool with potential users, a workshop was organized with participants from different part of Ericsson, all dealing with sustainability issues in their work. They were given an early version of PEEC and had 10 minutes to discover it before answering a short user experience questionnaire. The question we were trying to answer that way is: is the tool easy to understand without the help of any explanation or documentation? Four questions in the questionnaire were asking if the respondent had understood where to enter the inputs and how to interpret the results only with the help of the interface. Then, the respondents were asked about their feeling and could select concerns they were worried about with the version of the tool. Finally, they were asked to rate their overall satisfaction.

In total, seven people answered the questionnaire, and the results are presented in Subsection 4.6.2. The rest of the workshop was dedicated to an open discussion in order to collect general feedback.

4 Results

After explaining in the previous chapter our methods to build the tool, this chapter will describe the outcome of this work: PEEC, its purpose, structure, underlying models and use cases. For the sake of transparency and reproducibility, some sections are voluntarily technical. Yet, the details are not necessary to reach a general understanding of the tool.

4.1 From customer expectations to the purpose of PEEC

This section describes the scope and purpose of the tool, resulting from the analysis of customer expectations.

4.1.1 Customer requests for embodied emissions of telecommunication products

Our work is located at the intersection between two different conceptions and interests:

i. the LCA studies, as presented in previously mentioned international standards [12]–[14], seeking to perform comprehensive and consistent environmental analyses, including all the life cycle phases and a representative set of environmental indicators
ii. interests from the industry, as identified in the collected customer requests.

Figure 1 summarizes the purpose of these customer requests, as well as the type of environmental data asked. Two requests come from research institutes and ask for data for research projects on network environmental footprint. The remaining requests come from mobile operators, among which four are for company sustainability reporting, three are for a company project and one is an open discussion between operators and manufacturers on carbon emissions. Most of the requests are only focused in carbon emissions, which is the environmental indicator the most discussed and followed in politics, media and the industry.

It is interesting to observe that the requesters ask for different level of granularity in the data. If some only ask for an emission figure on a representative product, others query precise information on specific products. In fact, customers ask most of the time for as much information as possible, knowing the diverse level of maturity about sustainability of suppliers in the sector. They ask for full LCA or sustainability certificates if available, else estimations on the carbon footprint or material composition and manufacturing energy data.

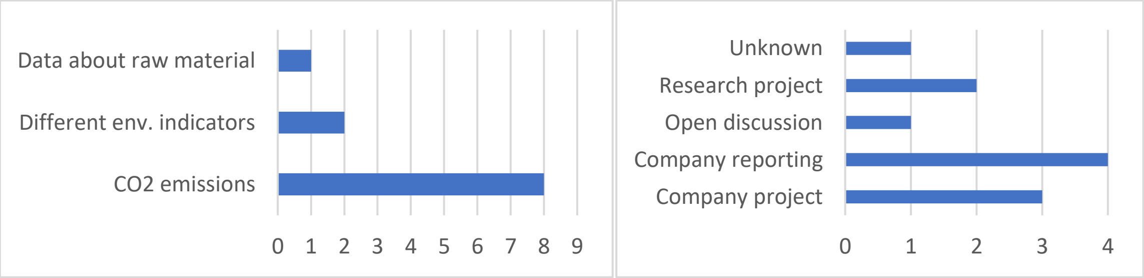


Figure 1: **Type of environmental data requested (left) and purpose of the customer request (right)**. The 11 customers' requests were collected in the context of this project by Ericsson sustainability team (see Section 3.1 for further details).

4.1.2 Purpose of PEEC

Considering the previous subsection, the purpose of the tool developed in this thesis has been defined as follows. PEEC is a parametric model for embodied emissions of telecommunication networks reflecting data sets made available by the telecom provider Ericsson. PEEC contains company specific data gathered from models and experience built along years of sustainability work and aims to enable the carbon footprinting of all network equipment sold by Ericsson. It’s a self-contained tool giving transparency on data and methods for the stakeholders. Intended users for this tool are primarily Ericsson Sustainability Research but also sale support, knowledgeable customers, and research partners.

Note that PEEC does **not** intend to be a full LCA of the product but rather a simplified version of it, covering only cradle-to-gate life cycle phases and only one impact category: global warming potential (see description of the scope in 4.1.3). Moreover, with the current data set, PEEC is intended to represent typical conditions within Ericsson operations and supply chain, rather than assessing the individual conditions of a specific product. In principal, however, it would be possible to adjust the PEEC data set to a specific product, but that is not the intended use of the tool and would only duplicate the work that would first need to be performed in a standard LCA tool such as GaBi.

4.1.3 Life cycle phases under scope

PEEC is providing a simplified way to estimate the embodied carbon footprint of mobile network products. By “embodied carbon footprint” (or “embodied emissions”, or “cradle-to-gate emissions”) is designated the greenhouse gases emissions associated with raw material acquisition, parts manufacturing and assembly of the assessed product. Packaging and transport along the supply chain are included, as well as support activities (R&D, sales, human resources, …) of the companies involved to the possible extent. Downstream activities like use stage and end-of-life of the product are excluded from the scope. See the system boundaries below in Figure 2.

For the sake of data transparency, the master’s thesis doesn´t reflect the latest hardware platform of Ericsson but refers to an earlier one, Radio Base Station (RBS) 6000, which allows for including more granular information regarding the product characteristics.

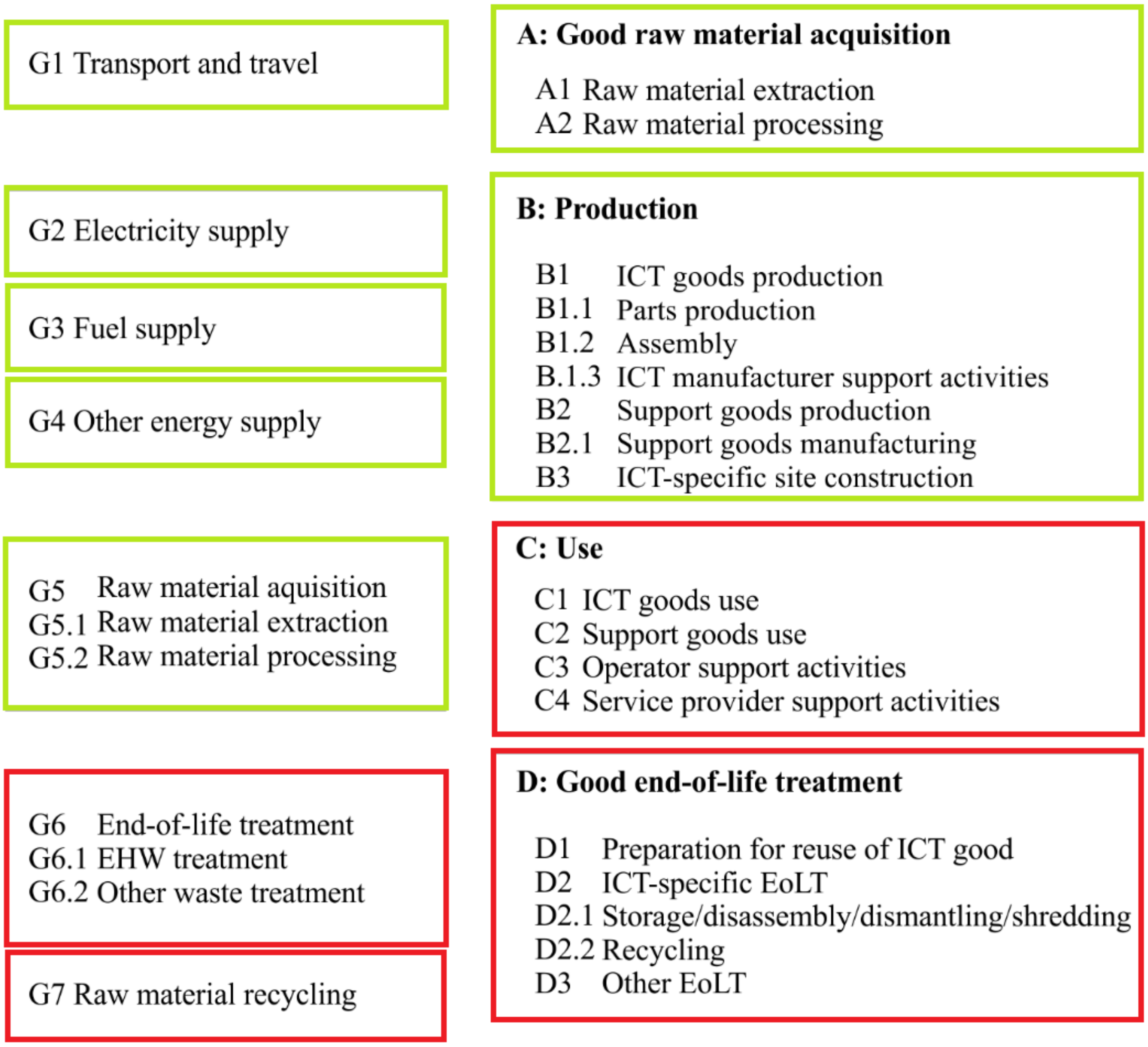


Figure 2: **Life cycle stages modelled by PEEC (in green) and excluded from the scope (in red)**. Reprinted from the LCA for ICT standard (Figure 7, [14]). "ICT manufacturer support activities" concerns only the providers of the final product (Ericsson in our case), and support activities from suppliers are included in their respective life cycle stage.

4.2 PEEC description

PEEC is built in MS Excel, which makes it easily accessible and modifiable. In order to allow the use of the tool by users with different levels of knowledge on the products, it follows the tree structure illustrated in Figure 3. The rest of this report uses the following terminology:

- '**Products**' refer to complete mobile network equipment (e.g. a fully equipped radio base station). Customers with little information on the hardware contained in the products can fill in their product configurations in PEEC product sheet (see 4.2.1).
- '**Modules**' refer to the main building blocks of mobile network equipment (e.g. a radio unit). It is at this level that the model for embodied emissions is build. To assess the carbon footprint of new products or to simulate the impact of a specific material or a manufacturing process on the whole life cycle, the user can use PEEC module sheet (see 4.2.1).
- '**Components**' are the small parts making up the modules (e.g. a transistor or a screw).

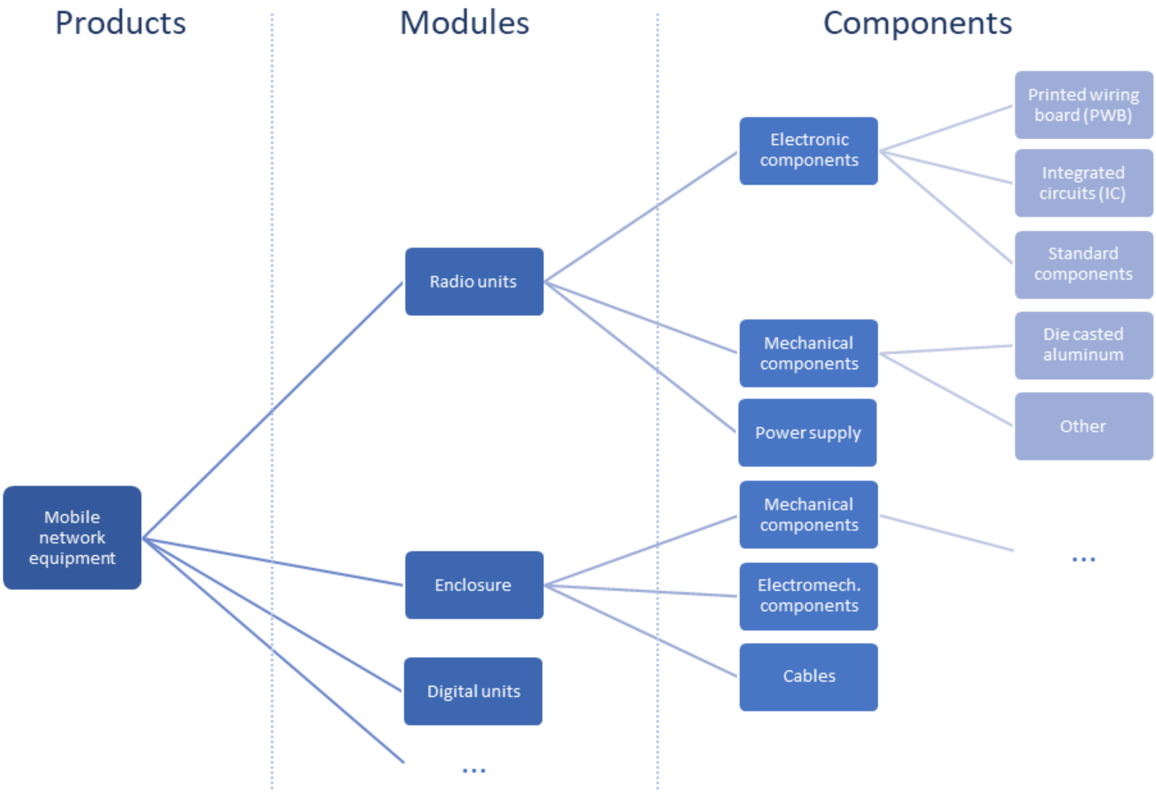


Figure 3: **Calculation hierarchy for the carbon footprint of products in the mobile network**.

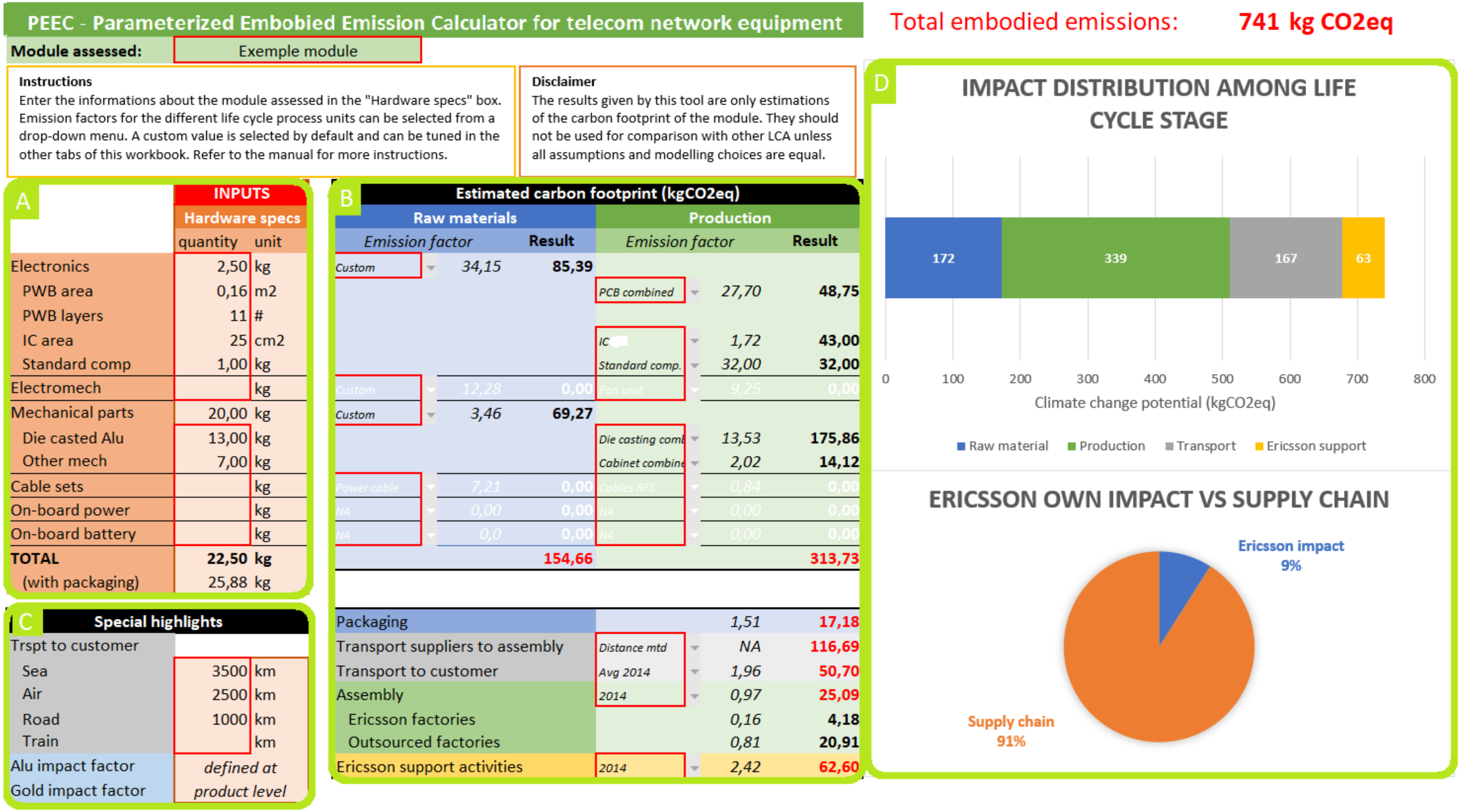
The default way to use the tool modifies only the product and potentially the module level. But for more detailed assessments by more advanced users, data and calculations can also be changed in the other sheets of the workbook. The different sheets are described more in detail in the following and a **full set of screenshots of the tool is attached in Appendix B**: Screenshots of PEEC.

4.2.1 PEEC product sheet

The product sheet is the highest level in PEEC. It contains a table with all the modules already assessed in the tool (to each of which corresponds a module sheet). The user can fill in quantities for every module, corresponding to a specific product configuration. The table simply gathers and sums up the embodied emissions results fetched from the module sheets. Results are then displayed as a graph similar to the one from the module sheet described further down.

4.2.2 PEEC module sheet

The module sheet is the most important building block of PEEC, giving an overview of the model, gathering the main inputs on the assessed module and displaying the results. A screenshot of PEEC module sheet is given in Figure 4. This sheet is organized in the following way. The hardware characteristics of the module are entered in the red boxes to the left (box A). Additional parameters (later called “special highlights”) can be specified in box C. Carbon emission calculations are performed in box B, using predefined values for emission factors (in italic) that can be selected from drop-down menus. Finally, the results are displayed in bold red and reported in two graphs (box D).



PEEC - Parameterized Embobied Emission Calculator for telecom network equipment

Total embodied emissions: 741 kg CO2eq

Module assessed: Exemple module

Instructions
Enter the informations about the module assessed in the "Hardware specs" box. Emission factors for the different life cycle process units can be selected from a drop-down menu. A custom value is selected by default and can be tuned in the other tabs of this workbook. Refer to the manual for more instructions.

Disclaimer
The results given by this tool are only estimations of the carbon footprint of the module. They should not be used for comparison with other LCA unless all assumptions and modelling choices are equal.

A

	INPUTS	
	Hardware specs	
	quantity	unit
Electronics	2,50	kg
PWB area	0,16	m2
PWB layers	11	#
IC area	25	cm2
Standard comp	1,00	kg
Electromech		kg
Mechanical parts	20,00	kg
Die casted Alu	13,00	kg
Other mech	7,00	kg
Cable sets		kg
On-board power		kg
On-board battery		kg
TOTAL	**22,50**	**kg**
(with packaging)	25,88	kg

B

Estimated carbon footprint (kgCO2eq)

Raw materials			Production		
Emission factor		**Result**	*Emission factor*		**Result**
Custom	*34,15*	**85,39**			
			PCB combined	*27,70*	**48,75**
			IC	*1,72*	**43,00**
			Standard comp.	*32,00*	**32,00**
Custom	*12,28*	**0,00**	*Fan unit*	*9,25*	**0,00**
Custom	*3,46*	**69,27**			
			Die casting comb	*13,53*	**175,86**
			Cabinet combine	*2,02*	**14,12**
Power cable	*7,21*	**0,00**	*Cables RFS*	*0,84*	**0,00**
NA	*0,00*	**0,00**	*NA*	*0,00*	**0,00**
NA	*0,0*	**0,00**	*NA*	*0,00*	**0,00**
		154,66			**313,73**

Packaging		*1,51*	**17,18**
Transport suppliers to assembly	*Distance mtd*	*NA*	**116,69**
Transport to customer	*Avg 2014*	*1,96*	**50,70**
Assembly	*2014*	*0,97*	**25,09**
Ericsson factories		*0,16*	**4,18**
Outsourced factories		*0,81*	**20,91**
Ericsson support activities	*2014*	*2,42*	**62,60**

C

Special highlights

Trspt to customer		
Sea	3500	km
Air	2500	km
Road	1000	km
Train		km
Alu impact factor	*defined at*	
Gold impact factor	*product level*	

Figure 4: **Screenshot of PEEC module sheet**. In this overview page, the main inputs can be entered. Estimated embodied emissions for every life cycle category of the assessed module are displayed in bold red and summarized in two result graphs. Calculations and data are fetched from the other sheets.

4.2.2.1 Inputs

The PEEC module sheet includes a number of input parameters (the red boxes, see Figure 4). They are parameters that have been identified either as key parameters to estimate the module cradle-to-gate carbon footprint more accurately, or as parameters of special interest to some potential users. The inputs are of three types that are described below: hardware characteristics, emission factors and special highlights.

Hardware characteristics (box A in Figure 4). This input category groups hardware characteristics of the module. The ICT LCA standard suggests a list of parts (that we will call "component categories" to match our terminology) to be taken into account when performing the LCA of an ICT product (see annex E [14]). Some of them are not relevant for mobile network products (screens, cartridge, …) and we merged some others into the same category (e.g. Electronics), resulting in the six component categories listed in Table 2. To each category is associated a set of characterizing parameters which are later used to evaluate the module carbon footprint.

Table 2: **List of hardware parameter inputs in PEEC.** The classification is adapted from the ICT LCA standard [14] and is similar to the component characterization method used in similar work (see Table 5.3 [16]).

Component category	Input parameters
Electronic components	- total mass of electronics (kg) - area of Printed Wiring Board (PWB) (m^2) - average number of PWB layers - area of Integrated Circuits (IC) (m^2) - mass of standard components (electronics other than PWB and IC) (kg)
Electromechanical components (mainly fans)	- mass (kg)
Mechanical components	- mass of die casted aluminum (kg) - mass of other mechanics (kg)
Cable sets	- mass (kg)
Power supply components	- mass (kg)
Battery	- mass (kg)

Raw materials and production emission factors (box B in Figure 4). The module's carbon footprint is estimated from the hardware specifications using emission factors representing typical conditions of the component categories. More specifically, the emission factors express the carbon intensity of the raw material or production phase of one unit of the corresponding component. For example, the component category 'cable sets' have a raw material emission factor given in $kgCO_2eq/kg$ capturing the carbon intensity of the acquisition of the raw materials needed for one kilogram of cable set.

To enable a more accurate representation, the user can select from different predefined values for emission factors, fetched in the other sheets. He or she can also create and select a custom value if more precise information is known about the module.

For further details on the emission factors and how they are derived refer to the model description (Section 4.3) and the data collection process (Section 4.4).

Special highlights (box C in Figure 4). A few additional inputs have been identified as being of interest for potential users during discussions and workshops. They have been put forward in the module sheet to make them easier to modify without heading to the other sheets. These inputs are

- the distance travelled by the module from the assembly factory to the customer (in km by sea, air, road and train),
- the emission factor for aluminum (in $kgCO_2eq/kg$ of aluminum),
- the emission factor for gold (in $kgCO_2eq/kg$ of gold).

The first input is specific to the company (and even customer) and changes substantially over time if mode of transportation changes which makes it of special interest to the customers. The second input is specifically highlighted because aluminum makes up for a good part of Ericsson products' composition and has a high emission factor that varies a lot depending on its provenance (country of extraction, virgin or recycled). Finally, the emission factor for gold is brought forward because it has been identified as having a large impact on the results, both in the sensitivity analysis of this work (see 5.1.2) and in previous studies [39]. However, gold is harder to impact by design (less options available).

4.2.2.2 Results and graphs

The embodied emissions estimated by PEEC for the studied module are displayed in the module sheet. Intermediary results are in dark bold and the derived contributions are in red bold ('Result' columns in box B, Figure 4). All the contributions are summed up in the grand total unit figure at the top of box D. They are also displayed below it as a stacked bar chart, split by life cycle stages matching their fill color in the sheet. The life cycle stages are the following:

- **Raw material (in blue)** accounts for module's raw materials and the intermediate and final packaging,
- **Production (in green)** accounts for the production and the assembly of the module's components,
- **Transport (in grey)** accounts for transport to customer and along the supply chain,
- **Ericsson support (in yellow)** accounts for the company's operational activities.

Further down, a pie chart represents the proportion of emissions that are attributable to Ericsson activities (this includes Ericsson support activities and Ericsson assembly factories).

4.2.3 Other sheets: background data and calculations

In addition to the product and module sheets, PEEC is composed of a few other necessary sheets. There is one sheet dedicated for each sub-model for embodied emissions: sub-model for raw material (RM), production (Prod), transport and packaging (Trsp&Pkg), and assembly and Ericsson's support operation (Asbly&Op Eri). They contain the data that is then used in the module sheet.

Finally, PEEC includes also a sheet for the creation of drop-down menus and another one listing the data sources.

4.3 Model description for mobile network modules

In this section we detail how embodied emissions are calculated in PEEC at a module level based on the hardware specifications and for each phase of the life cycle.

4.3.1 Raw material

For each of the six component categories, in the module sheet, the contribution of the raw material stage to the carbon footprint is simply obtained by multiplying the total mass of components in the component category by the corresponding raw material emission factor.

$$RM\ impact_{compo\ category} = mass_{compo\ category} * emission\ factor$$

In other words, all the information on the underlying material composition is embedded in the emission factor (see calculation method part 4.4.1) which is derived in the sheet 'RM'. This emission factor includes the mining and refinery of the raw materials, along with their transport to suppliers.

Emissions from packaging are also reported as raw material emissions but they are calculated along with emissions from transport (see 4.3.3 for further details).

4.3.2 Production

4.3.2.1 Electromechanics, Battery, Power Supply and Cable sets

Greenhouse gases emissions from production processes are calculated in a similar fashion as raw material for the Electromechanics, Battery, Power Supply and Cable sets categories. For these four categories, the total mass of components is multiplied by the corresponding emission factor from the underlying sheets.

$$production\ impact_{compo\ category} = mass_{compo\ category} * emission\ factor$$

4.3.2.2 Mechanical parts

For production of mechanical parts, we differentiate between the production of die casted aluminum (carbon intensive and often used in Ericsson products) and other mechanicals (steel frames, bolt, screws, …). For this reason, there is one emission factor for each of these two categories, and their contributions are summed up.

4.3.2.3 Electronics

For production of electronics, the method is different. According to similar studies ([33], [39], [40] or GaBi models for electronics presented in Appendix A: GaBi carbon emission data for PWB and IC of this report) and in line with [13], environmental burden from electronics production does not scale by weight but rather by area of printed wiring boards (PWB) and integrated circuits (IC). Our model separates the impact in three parts: production of the PWB, production of the IC dies and production of other electronic components (resistors, capacitors, IC package, …).

$$impact_{Electronics} = impact_{PWB} + impact_{IC} + impact_{std\ comp.}$$

Impact from PWB is calculated as follow, with the area of PWB and the average number of PWB layers as key parameters:

$$impact_{PWB} = area_{PWB} * \#layers * emission\ factor_{PWB}$$

For the IC, the die area is the scaling parameter. Thus, the impact of IC production (excluding IC package):

$$impact_{IC} = die\ area_{IC} * emission\ factor_{IC}$$

The remaining electronic components (everything else but PWB and IC die) are scaled by their weight:

$$impact_{std\ comp.} = mass_{std\ comp.} * emission\ factor_{std\ comp.}$$

Emissions from final assembly are also reported as production emissions but they are calculated along with ICT manufacturer support operations (see 4.3.4 for further details).

4.3.3 Transport and packaging

4.3.3.1 Packaging

Packaging is modelled in PEEC through packaging factors. The mass of components in a component category is scaled with the corresponding factor to get the mass of components plus packaging. We take into account both inbound packaging (used to ship the components from the suppliers to the assembly factory) and outbound packaging (to ship the module from assembly to customers). An emission factor (in kgCO$_2$eq / kg of packaging material) is applied to the mass of packaging to account for their emissions. Thus, the equations below:

$$impact_{outbound\ pkg} = mass_{module} * (pkg\ factor_{module} - 1) * emission\ factor_{pkg}$$

$$impact_{inbound\ pkg} = \sum_{compo\ ctgies} mass_{compo\ ctgy} * \left(pkg\ factor_{compo\ ctgy} - 1\right) * EF_{pkg}$$

4.3.3.2 Transport

PEEC takes into account emissions both from inbound (from suppliers to module assembly) and outbound (from assembly to customers) transport. The transport of raw materials from mining sites to suppliers is not modelled directly but included in the raw material emission factors. The user can select from two different calculation methods for transport emissions: a top-down approach based on annual transport emissions averages from the company reporting or a bottom-up approach based on distances travelled.

Method based on annual transport emissions. With this method, inbound and outbound emissions from transport are estimated through annually reported transport emission of Ericsson overall, averaged per kilogram of delivered goods. This is a rough estimation, somehow capturing the reality of the company's logistic chains, but not the specific conditions of the module assessed or of a specific customer.

Method based on distances. With this method, to calculate the emissions related to the inbound transport of a component, we multiply the mass of component plus packaging with the travelled distance and an emission factor representing the means of transport (sea, road, air and train, as advised by the standard [14], annex D). The same method applies for the emissions related to outbound transport. The emission factors used for each means of transport are given below in Table 3.

Table 3: **Emission factors for transport**, as used in Ericsson sustainability reporting [41]. The scaling unit is ton-kilometers.

	Sea	Road	Air	Train
Emission factor (kgCO$_2$eq/tkm)	0,012	0,073	0,650	0,029

4.3.4 Assembly and ICT manufacturer support operations

'Assembly' in the model refers to the last activities performed in the production chain of the module: mounting of electronic components on the printed board, assembly inside the mechanical frames and module testing. Sometimes, modules are also assembled together into the final product in the factories, this would also be counted here. 'ICT manufacturer support operations' refers to activities specific to the assessed good (i.e. research and development, sales, marketing) but also other general organizational activities in the company allocated to the assessed good (i.e. human resource, communication, financial department). The ICT manufacturer in the model is Ericsson.

Given the available input parameters entered in PEEC and the challenges associated with the identification and allocation of the activities specific to the studied product, a top-down approach is chosen to model assembly and ICT manufacturer support operations. These life cycle stages are taken into account through averages per kilogram of product derived from annual reports (see 4.4.3.3 for further details). This allocation is discussed in the Discussion (part 5.1.1.5).

4.4 Data collection

As part of this master's thesis, predefined emission factors have been calculated and entered in PEEC. They are based on existing models for representative network products of Ericsson's RBS 6000 generation of network equipment, developed in a company internal project [42]. For this reason, the thesis made use of these models built in the LCA software GaBi [43], which were accessible along with all datasheets and documents used to create them.

4.4.1 Raw material

Raw material acquisition stage was modelled by combining materials declarations data of Ericsson products and ecoinvent materials data sets as detailed below.

4.4.1.1 Data collection method

For a given component category, the method chosen to assess its raw material emission factor follows these steps:

i. **Getting the material declaration of a representative product through Ericsson internal software**[3]. The available data emerge from full materials declarations provided to Ericsson by their suppliers.
ii. **Cleaning the data.** Removing packaging materials, averaging over different suppliers of the same components[4]. For some components where materials

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[3] Ericsson is demanding full material declarations from its suppliers applying IEC62474 and have thus access to a large data set with detailed materials information (https://std.iec.ch/iec62474).

[4] For technical information on how steps (i) and (ii) are performed with Ericsson tools and Excel macros, refer to [44]

declarations from suppliers were missing or considered to be of low quality, their materials composition was estimated by Ericsson experts based on similar products to avoid data gaps.

iii. **Sorting materials into a short list of material** (see 4.4.1.2 for further information). In the data set obtained before, some materials are trade secret, unknown (represent data gaps) or do not belong to any category in the short list. These will be dealt with in step (vii).

iv. For each known material, **multiplying its mass in the final product by an input factor** (see Table 4 column 3) capturing the extra material needed as input and wasted during the manufacturing process. These input factors are estimates based on discussions with suppliers and Ericsson knowledge.

v. **Multiplying the input mass obtained this way by an impact factor** telling how much CO_2 emissions are related to the extraction of this material based on Table 4 column 2 and 4.

vi. Summing up the contribution of each material.

vii. **Extrapolating the result to take into account unknown, trade secret or unclassified materials**. The extrapolation is done linearly: with p the proportion of the product mass that could be categorized at step (ii), the result will be multiplied by $1/p$ to get the final result. We are then making the strong assumption that the trade secret, unknown and unclassified materials have the same impact as the average known material. This assumption is discussed in 5.1.1.1.

The method described above is summarized below in Figure 5.

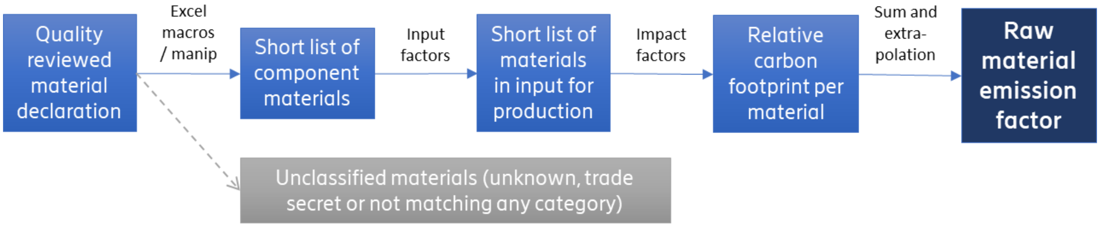

Figure 5: **Method for calculating the raw material emission factors in PEEC**.

4.4.1.2 The short list of materials

The short list of material along with input factors and emissions factors chosen for each material is provided in Table 4. Material declarations can contain more than 300 different materials. The short list intends to group together the most common materials in mobile network products as well as valuable materials ('VM' in Table 4), present in small quantities but with a significant environmental impact. Some material are necessarily discarded but for each module studied, always less than 9% (4% in two thirds of the cases) of its total mass had a known composition which could not be classified in any of the categories of the short list (see 5.1.1.1 in the Discussion). These unmodelled materials are extrapolated along with the unknown and trade secret materials.

Carbon footprint data for raw materials was obtained through the ecoinvent database [45]. For each material, the 'market' dataset for this material was chosen. It is a cradle-to-gate value, representing the mix of suppliers of this material in the market[5] in the current year (2019 in ecoinvent 3.6) and including average values for transport. The global market share was selected when available (geographical area 'GLO' in ecoinvent), else the 'rest of the world' ('RoW') value, excluding Europe. The impact factor was obtained by using the ReCiPe Midpoint (H) climate change indicator in GaBi[6].

Table 4: **Short list of materials** applied to simplify the raw material carbon footprint assessment phase. 'VM' stands for Valuable Material.

Material or material category	**Impact factor ($kgCO_2e$/kg)**	**Input material factor**	**Name in ecoinvent 3.6 [45]**
Iron/steel	1,74	1,3	GLO: market for cast iron
Aluminum	19,01	1,1	RoW: market for aluminium, primary, ingot
Copper	4,76	1,25	GLO: market for copper
Zinc	3,05	1,3	GLO: market for zinc
Chrome	26,8	1,3	GLO: market for chromium
Nickel	13,7	1,3	GLO: market for nickel, 99.5%
Manganese	3,31	1,3	GLO: market for manganese
Magnesium	28,	1,1	GLO: market for magnesium
Tin	10,5	1,1	GLO: market for tin
Silicon	82,2	1,1	GLO: market for silicon, electronics grade
Plastics	2,5*	1,25	Not from ecoinvent. See note below.
Epoxy	4,49	1,25	GLO: market for bisphenol A epoxy based vinyl ester resin
Glass wool	2,66	1,4	GLO: market for glass wool mat
Paper/wood	0,83**	2	RoW: market for plywood, for indoor use
VM - gold	49400	1,1	GLO: market for gold
VM - indium	131	1,1	GLO: market for indium
VM - palladium	11500	1,1	GLO: market for palladium
VM - platinum	70600	1,1	GLO: market for platinium
VM - silver	519	1,1	GLO: market for silver
VM - tantalum	284	1,1	GLO: market for tantalum, powder, capacitor-grade
VM - titanium	30,3	1,1	GLO: market for titanium, primary
VM - tungsten	5,43	1,1	GLO: market for tungsten concentrate***
Antimony	8,80	1,1	GLO: market for antimony
Cobalt	11,38	1,1	GLO: market for cobalt

* The impact for plastics is based on expert opinion considering the composition of plastics in use in Ericsson products
** Assuming a volumic mass of 600kg/m3
*** The value for tungsten comes from ecoinvent 3.7 (it was not available in ecoinvent 3.6)

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[5] It is assumed that this value reflects a mix of virgin and recycled materials, but this is not clarified in the ecoinvent documentation. For more explanation on ecoinvent 'market' datasets, see www.ecoinvent.org/support/faqs/methodology-of-ecoinvent-3/what-is-a-market-and-how-is-it-created.html

[6] The ReCiPe LCA methodology is one of the life cycle impact assessment methodology available in GaBi. More information can be found in GaBi documentation: www.gabi-software.com/support/gabi/gabi-lcia-documentation/recipe/

4.4.1.3 Raw material emission factors

By following the method described in 4.4.1.1, starting from the material declarations of reference products, we derived the emission factors for component categories of some hardware, appended below in Table 5.

Table 5: **Raw material emission factors used in PEEC.** All emission factors were calculated from the material declaration of the reference products according to the described data collection method.

Component category	Hardware type	Raw material emission factor ($kgCO_2e/kg$)	Reference product
Electronics	Radio unit (RU)	34,15	Typical RU in RBS6000
	Digital unit (DU)	37,76	Typical DU in RBS6000
	Remote radio unit (RRU)	68,85	Typical RRU in RBS6000
Electromech	Fan, indoor	12,28	Fan in RBS 6201
	Fan, outdoor	6,20	Fan in RBS 6102
Mechanicals	Indoor cabinet	3,46	Cabinet 6201
	Outdoor cabinet	12,92	Cabinet 6102
	Radio unit	20,66	see above
	Digital unit	21,76	see above
	Remote radio unit	21,87	see above
	Main unit of main remote base station	6,15	RBS 6601
Cable sets	Coaxial cable	7,66	Cables in RBS 6201
	Power cable	7,21	Cables in RBS 6201
	Signal cable	7,78	Cables in RBS 6201
Black box modules	Power distribution unit	7,16	PDU 02 01
	Power supply unit	30,40	PSU AC 02
	Transport connectivity unit	30,01	TCU 02 01

4.4.2 Production

Emission factors for production processes were extracted from the existing models in the LCA software GaBi [43] as further described below.

4.4.2.1 Description of the existing production data in GaBi

GaBi models for production were built by Ericsson upon collection of primary data from suppliers in 2013-2014. There is one model per component type, built per reference unit of component. For each of them, a questionnaire was sent to one or several representative suppliers in order to collect data on key manufacturing processes (e.g. drilling, melting, surface treating etc.). Data collected included energy consumption, waste treatment, emission to air and water and outbound transport associated to the manufacturing processes. The relevant processes were then selected from the GaBi/ecoinvent databases according to the geographic location of suppliers if available, otherwise the global model was selected. Localization greatly influences the results for electricity. The country-specific electricity mixes were chosen wherever it was possible, else the European or global alternative. According to [42], LCA standards ([12]–[15]) were considered as far as possible throughout the whole data collection process.

4.4.2.2 Emission factors

Emission factors extracted from the internal Ericsson models in GaBi are given below in Table 6. Again, ReCiPe Midpoint (H) climate change indicator was used to estimate the global warming potential of the production processes modelled.

Table 6: **Production emission factors used in PEEC**. The emission factors were extracted from GaBi models [42] as explained above.[7] In the right column, the ratio of the footprint attributable to electricity use in the models is given.

Hardware type	Reference unit	Production emission factor ($kgCO_2e$/reference unit)	Footprint due to electricity
Electronics - PWB	m^2 x #layers	27,700	85%
Electronics - IC	cm^2 of die	1,720	97%
Electronics - standard components*	kg	32,000	NA
Electromech - fan unit*	kg	9,250	NA
Mechanicals - die casted aluminum	kg	13,528	97%
Mechanicals - others	kg	2,017	69%
Cable sets	kg	0,837	62%
Black box - power supply unit	kg	1,747	98%
Black box - power distribution unit	kg	2,405	99%

* Because there was no model for standard electronics components and fan developed for RBS6000, the data gaps were filled with values from internal models.

4.4.3 Transport and packaging

Below are the emission factors and data used for accounting packaging and transport.

4.4.3.1 Packaging scaling factor

Still building upon the previous study for RBS 6000 [42], PEEC was filled by default with packaging scaling factor estimated then. We take 3 as a packaging factor for electronic components and 1,15 for all other components and the final product. It means for example that packaging is estimated to weigh 15% of the product mass and impacts of the packaging is added on top of product impacts.

4.4.3.2 Average packaging emission factor

To estimate the carbon footprint of packaging, we assumed the same average packaging composition for all components and the final product, given in Table 7. The Ericsson GaBi model corresponding to this composition was used to calculate the climate change potential, resulting in an **emission factor of 1,51 $kgCO_2eq$ per kilogram of packaging material**.

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[7] As the Ericsson models included outbound transport, the original values were recalculated as that is treated separately in PEEC.

Table 7: **Average packaging material content**, as in [42]

Packaging material	Quantity per kg of packaging
Polyethylene film	0.115 kg
Polyurethane flexible foam	0.115 kg
Corrugated board	0.15 kg
Plywood, outdoor use	50 cm^2 (0.3 kg)
Steel sheet, galvanized	0.017 kg
EUR-flat pallet	0.012 p (0.3 kg)
Average packaging material	1 kg

4.4.3.3 Average transport emission factors

At Ericsson, the transportation of products to customers is performed by logistics service providers like DHL or UPS. The average outbound transport emission factor is obtained by dividing the product transport emissions reported in Ericsson's annual report [41] by the total mass of transported products reported to Ericsson by the service providers. See figures further down in Table 9.

Emissions from inbound transport are not calculated and reported annually. There are still large data gaps to trace the transport flows from the suppliers to Ericsson. Nonetheless, an estimation have been done for the year 2019 in a recent master's thesis [46]. With this estimation, the average inbound transport emission factor could be calculated as above (see also Table 9).

4.4.3.4 Distances for transport

The distance model for transport would ideally require precise and product-specific geographical data which is challenging given the dynamic conditions of production and distribution activities. In our work, we use the localization of the representative suppliers that provided the production process data (see 4.4.2.1) and the mode of transportation they declared for their products. Then, we use the localization of assembly factories to estimate an average travel distance for each component. These average travel distances are given in Table 8.

Table 8: **Average travel distance from suppliers to assembly.** These are fictive distances, as if every representative supplier was shipping components to every assembly factory, based on the relative use of each and the declared mode of transportation.

Component type	Sea (km)	Air (km)	Road (km)
Electronics	0	7913	277
Electromech	8043	0	1332
Mechanicals - die casted aluminum	0	7807	247
Mechanicals - others	13507	0	883
Cables	1866	267	3199
Power supply	14750	0	250
Battery	7951	0	457

4.4.4 Assembly and ICT manufacturer support operations

4.4.4.1 Assembly

In Ericsson's production chain, assembly is partly performed in its own factories and partly outsourced to other electronics manufacturers. The average figure for module assembly is obtained by dividing total carbon emissions from Ericsson factories and carbon emissions from outsourced factories by the total weight of product in output of these factories (see Table 9). Support activities from these outsourced companies are included to an unknown extend, depending on how they report their carbon emissions.

To take into account the carbon emissions associated with Ericsson support activities, emissions from Ericsson factories are subtracted from the "Ericsson Facilities, Travel and Commuting" figure publicly reported every year in the annual report [41]. By doing that, we avoid double counting the assembly phase. As of today, it is assumed that 50% of Ericsson's activities are attributable to product and software development and sale. They are counted in the model as embodied emissions. The other 50% of Ericsson's activities concerns managed services and network roll-out. They would rather apply to later life cycle stages, like use stage operation and maintenance activities and are thus excluded from scope of PEEC.

4.4.4.2 Emission factors

Both the assembly and support operation figures are annual figures and the reference year to be used can be selected as a parameter in PEEC. Figures for the year 2014 are given in Table 9.

Table 9: **Emission factors for transport, final assembly and support activities** and background emission data for the year 2014.

Reported quantity	Value	Source
Carbon emissions Ericsson factories	16 ktonCO$_2$eq	Internally reported
Carbon emissions outsourced assembly factories	80 ktonCO$_2$eq	Estimations based on company reporting
Carbon emissions "Ericsson Facilities, Travel and Commuting"	495 ktonCO$_2$eq	[41]
Carbon emissions "Product transport"	204 ktonCO$_2$eq	[41]
Carbon emissions inbound transport*	81 ktonCO$_2$eq	[46], year 2019
Total weight of packaged products shipped from assembly factories to customers	99 kton	Internally reported
Emission factor support activities, (50% allocated to products delivered)	**2,42 kgCO$_2$eq / kg packaged product**	**Calculated from above**
Emission factor final assembly	**0,97 kgCO$_2$eq / kg packaged product**	**Calculated from above**
Emission factor outbound transport**	**1,96 kgCO$_2$eq / kg packaged product**	**Calculated from above**
Emission factor inbound transport	**0,82 kgCO$_2$eq / kg packaged product**	**Calculated from above**

* Inbound transport is not reported annually. This value is from an estimation made for the year 2019. The value for 2014 is probably higher.

** The carbon footprint figure for product transport has been reduced by 10kton before dividing by the total weight, to exclude the transport of unrelated products

4.5 Example use of PEEC: embodied emissions of radio access network products

In the previous sections, we described the model for embodied emissions and its implementation in PEEC at a **module** level (radio units, digital units, cabinets…). Some users (e.g. Ericsson's customers or customer support organization) might want to provide input at a higher level and assess the embodied emissions of fully equipped base stations. We describe in this section how PEEC can be used for this purpose and disclose as an example embodied emission results for the Ericsson's RBS 6000 generation of network equipment.

4.5.1 Description of RBS 6000

RBS 6000 generation of Radio Access Network (RAN) equipment was Ericsson RAN solution sold to customers during the last decade. It supports GSM (2G), CDMA/WCDMA (3G), and LTE (4G). The base stations, operated by the mobile operators, are generally composed of a cabinet containing internal hardware and connected by cables to antenna towers, sending and receiving the signal. Inside the cabinet are

- internal Radio Units (RU) that convert radio waves to and from digital signals,
- Digital Units (DU) that provides switching and processing of the digital signals
- and various Power Supply Units (PSU), Power Distribution Units (PDU) and transmission equipment.

Up on the tower can be mounted

- Remote Radio Units (RRU): an outdoor version of RU,
- antennas: transceiver of the radio signal, connected to an RU or RRU
- and/or Antenna Integrated Radio (AIR) units, combining both.

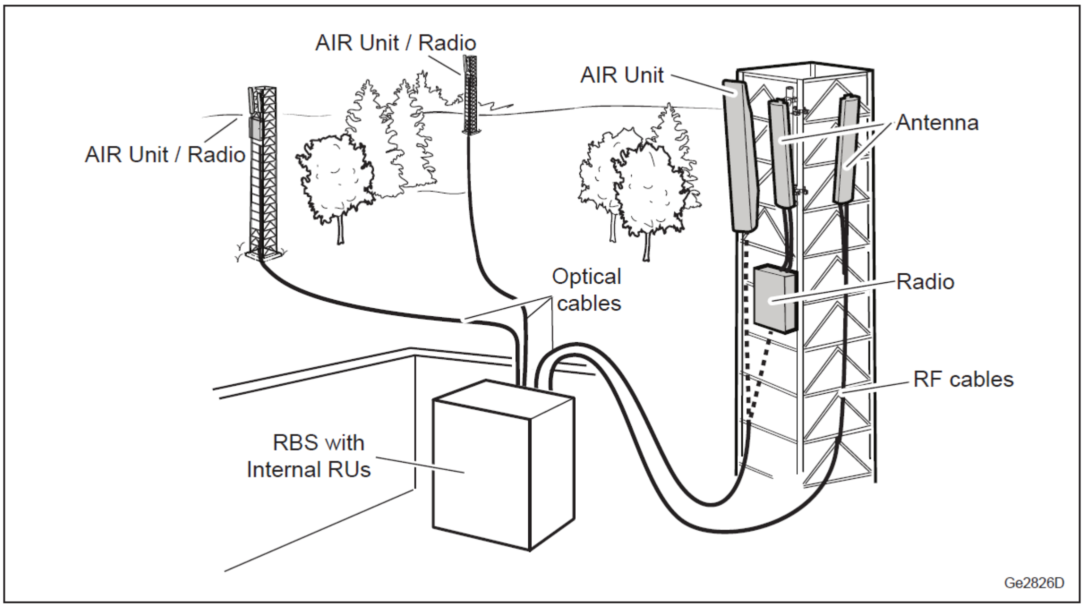

Figure 6: **Operating principle of a Radio Base Station (RBS)**. The figure illustrates for the example a hybrid configuration with radios both inside and outside the cabinets. The configuration chosen in this thesis (and described after) includes only internal radio units. Figure from [47].

4.5.2 PEEC inputs for RBS 6000

Hardware characteristics were collected on different modules composing a typical RBS 6000 and filled in PEEC. These figures were obtained from technical information [47], previous teardowns and expert judgment and should only be considered as an example. They are reported below in Table 10. Some modules in the RBS are not manufactured by Ericsson, they should ideally still be treated in the same way as the others in the model, but we consider them as black-box modules because of lack of data.

Table 10: **Hardware characteristics of typical RBS 6000 modules**. The rows in the table match the hardware parameter inputs in PEEC listed in Table 2.

	Indoor cabinet	RU	DU	RRU	PSU	PDU
Electronics (kg)		1,54	1,41	1,85	Black-box module	Black-box module
PWB area (m^2)		0,17	0,16	0,20		
Average PWB layers		11	11	11		
IC die area (cm^2)		25	41	25		
Standard components (kg)		0,60	0,70	0,80		
Electromechanical components (kg)*	2,61**					
Die casted aluminum (kg)	1,72	4,20	1,45	16,00		
Other mechanics (kg)	78,48	1,60	0,03	7,00		
Cables (kg)	5,40					
Power supply components (kg)***						
Battery (kg)						
TOTAL mass (kg)	**88,21**	**7,34**	**2,89**	**24,85**	**2,30**	**2,40**

* In this example, this category includes only fans. Connectors are counted as standard electronic components and cable assemblies as cable sets.

** Corresponds to 3 radial fans of 870g each.

*** In this example, power units on the printed board were counted as standard electronic components.

RBS 6000 is a modular solution that could be set up for different usages. The configuration (i.e. set of modules chosen) depends on the generation(s) of mobile network covered by the base station, the targeted maximum bandwidth and network coverage, the climatic conditions, the quality of power supply in the area, etc. Typically, an indoor base station is first installed at half its capacity, giving room for upgrade if needed in the future. This is the configuration we consider in our example:

- **1 indoor cabinet** with cable sets and fans[8]
- **6 radio units** out of the 12 slots available
- **1 digital unit**
- **3 power supply units**
- **1 power distribution unit** distributing the power to the modules in the cabinet

Transmission equipment modules (transport connectivity units, routers or mini-links…), which forward the data to nearby hubs or to the core network are cut-off. In order to be operational, an indoor base station also needs other equipment on site: container, tower, antennas, back-

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[8] In this Master's thesis, it has not been clarified whether the figures for cabinets (hardware characteristics in Table 10, raw material in Table 5 and production in Table 6) include switches, power connection filters, bus-bars, etc.

up power and batteries… These "site equipment", outside of the cabinet, are excluded from the scope.

Apart from the hardware characteristics, we remind that emission factors have to be selected as input in PEEC (see screenshot from the module sheet Figure 4). For raw material and production emission factors, the corresponding ones reported in Table 5 and Table 6 were chosen. Inbound transport is accounted using the method based on distances, with the average travel distances provided in Table 8. Lastly, the values for the year 2014 were selected for outbound transport, assembly, and support activities (see Table 9).

4.5.3 Embodied emission results

After having filled in the hardware characteristics and emission factors for every module of the aforementioned configuration in the dedicated module sheets, quantities for each module were entered in the product sheet. The numerical results output by PEEC are appended below in Table 11.

Table 11: **Embodied emissions of a representative configuration of RBS 6201**, Ericsson's previous generation of RAN base station, as calculated by PEEC with the data described before.

			Climate change potential (kgCO_2eq)				
Modules	**Qty**	**Mass in product (kg)**	**Raw material**	**Production**	**Transport**	**Ericsson support**	**Total**
Indoor cabinet	1	88,21	389	309	233	245	**1175**
RU	6	44,04	1080	1086	392	123	**2681**
DU	1	2,89	91	163	37	8	**299**
PSU	3	6,90	211	12	2		**225**
PDU	1	2,40	18	6	1		**24**
Total		**144,44**	**1789**	**1576**	**664**	**376**	**4405**

In this case, the differences between these results and full LCA results are rather limited as the data used in the tool was originally collected for an LCA of the example-product. Differences are mainly due to the simplification of the material compositions. However, for any other product, uncertainties would increase if emission factors are reused as such without updating the material compositions, production processes and travelled distances.

In this example, **the embodied carbon footprint calculated by PEEC for the base station under scope is of 4,4 tons of CO_2eq**. Additionally, it informs the user on the relative contribution of each of the composing modules. Here, the radio units are responsible for more than half of the embodied carbon footprint.

More interestingly, the user is given the possibility to investigate deeper by heading to the underlying module sheets and visualize transparently where the results come from. In this example, he or she would find out that the die casted aluminum frames of the radio units make up a good part of its embodied emissions, along with the production of electronics.

The user can also dynamically change the quantities in the product sheet, and the hardware characteristics or emission factors in the module sheet to study the impact on the results. For even more detailed analysis, raw material compositions or impact factors can be modified in the other sheets, as well as emissions factors for production processes, transport, assembly and support operations if the user has access to precise information of the supply chain of the specific product. In more general terms, PEEC is in fact a framework for emission assessment and all the assumptions can more or less easily be changed. It is to the responsibility of the user to ensure that eventual modifications are justified.

Finally, PEEC also displays the relative impact of each of the embodied life cycle stages of the product (last row in Table 11 or graph in Figure 7). Among embodied emissions, the raw material acquisition stage is the major contributor (41%), closely followed by the production stage (36%) then transport (15%) and Ericsson support operations (9%). Once again, note that other parts of the life cycle like use phase and maintenance, operators' support operation, and end-of-life are not under the scope of the tool. To give an idea to the reader and put these results in context, embodied emissions are generally estimated to represent 10 to 15% of the use phase emissions for a radio base station (assuming 10 years of use and a global electricity mix, according to Ericsson internal data sharing policy to support operator scope 3 reporting [48]).

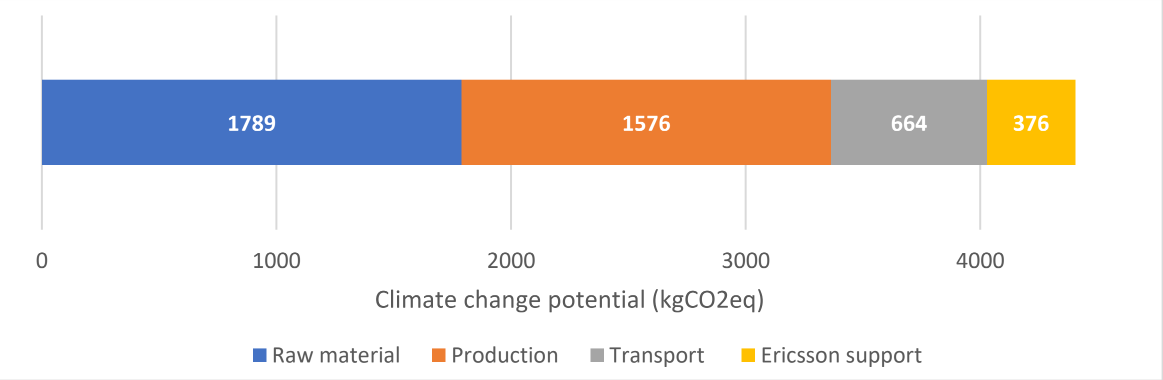

Figure 7: **Distribution of the embodied emissions of RBS 6201 on the different life cycle stages**.

4.6 Usability and use cases of the tool

The previous example gave an idea of the capabilities of the parametric model to make environmental assessment easier and more accessible to stakeholders. This section presents our efforts to make PEEC a usable and concrete lever for sustainability action.

4.6.1 Usability

Ergonomics. PEEC has been designed to have an intuitive structure and user interface. For the embodied emissions assessment of a mobile network module using the method described in this report, main inputs and results are gathered in one sheet, adapted for a computer screen (see Figure 4). It provides clarity and transparency. The decomposition of the assessed module in component categories to which corresponds hardware characteristic parameters, the basis of our assessment method, is clearly visible (Figure 4, box A). Red borders are used to indicate which cells are to be modified by the user. Italic is used for emission factors whereas results are in bold.

In addition, a color code is used throughout the Excel workbook to visualize the life cycle stages: raw material is in blue, production in green, transport in grey and ICT manufacturer support operations in yellow. These colors are applied to the impact distribution graph, to the background calculation tabs and to all the cells that have to do with one specific life cycle stage.

Flexibility. The choice of MS Excel as a software for the tool is a deliberate choice. It is a universal support in the sense that almost everyone has it and knows how to use it.

Consequently, PEEC remains flexible and can be adapted to the expected use. Users can lock cells or even entire sheets to avoid misuse, they can create copies of some sheets or the workbook itself and modify or update background data.

Emission factors derived in calculation sheets are sent back to the module sheet and can be selected via drop-down menus (see illustration Figure 8). That way, the user can pick the value that corresponds the most to the situation or create a new one.

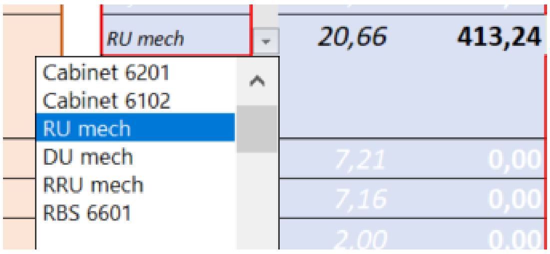

Figure 8: **Drop-down menu to select which value calculated in other sheets should be used.**

Transparency. One more strength of our implementation is that it brings transparency on the underlying model and data. Once again, the module sheet gives altogether an overview of the inputs, results, and methods of calculation without having to read any documentation or being an expert in life cycle assessment. The user is free to read the formulas and the Excel workbook is a self-contained tool that does not need any external data.

To make it possible to trace the source of the data, comments, notes, and references are left in the relevant cells.

4.6.2 User review workshop

A workshop was organized halfway through the thesis to get qualitative feedback on a first version of PEEC (see Section 3.4 in the Methods). Most of the participants had never seen the tool before and some were not even used to environmental assessment. Yet, their feedback on on-boarding experience after 10 minutes of trial were generally positive. It confirmed to us that the graphs were easy to understand and the inputs intuitive to find. As an outcome of this workshop, we clarified the results that were used to display the graphs and made the drop-down menus more visible. Some other small details could also be identified and corrected. Moreover, the session was a great opportunity to trigger discussion and interest among stakeholders and potential future users.

Another interesting outcome was to learn about the concerns around the usage of PEEC among the participants. A multiple-choice question was included in the user experience questionnaire that the participants had to fill after the 10 minutes trial. The answers to this question are given in Figure 9. If it is only qualitative results, it remains interesting to note that the participants are more worried by the tool not being simple enough to use and understandable for the users than getting in output wrong or unjustified results. This can be explained by the fact that the respondents are working inside the company and are confronted to questions related to the embodied emissions of mobile network products. As a result, their primary concern is to have an actionable way to answer them. Moreover, at the time of the workshop, the product level of PEEC was not yet build. We hypothesize that this higher-level view could help tackling these concerns. All the same, the results of Figure 9 highlight the need to pay attention on avoiding wrong usage of the figures produced by PEEC, which remain in the first place approximate figures.

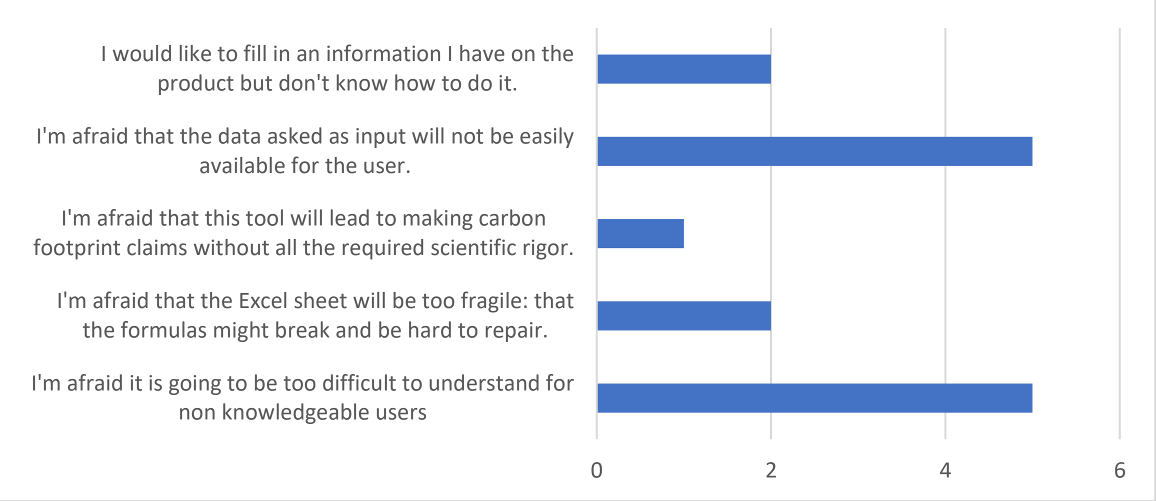

Figure 9: **Concerns about the use of PEEC in the company**. The 7 respondents were asked during the workshop to select from a list of 5 answers all the statements that they agree with. Note that we did allow them to enter other concerns out of this list.

4.6.3 Use cases for the company

We believe that the tool developed in this thesis and its future versions will be very useful for Ericsson, Ericsson's customers and other researchers in the field. The tree structure provides abstraction levels that allow a use of it for different purposes at different parts of the company. Table 12 summarizes the use cases foreseen by the author for PEEC.

Table 12: **Use cases for PEEC.**

Use case		Expected user	How?
1	**Helping mobile operators' scope 3 reporting**	Customers, sales support	By using the product level with up-to-date and validated data
2	**Answering customers questions and support monitoring of targets**	Ericsson sustainability team	By using the tool to make simulations or extract previously calculated data
3	**Research projects**	Research partners	By providing the full tool, its method and data
4	**Increasing transparency on assessment methods and assumptions**	Ericsson Sustainability Research Team	By publishing publicly this report and making the tool available to other parts of the organization / externally
5	**Testing different scenarios**	Product design, sustainability teams	By using the module level and tuning parameters (weight, impact factors, transport distances…)
6	**Contributing to a better understanding of ICT sector emissions**	Ericsson Sustainability Research Team	By keeping the tool updated with new products

Use cases 1, 2 and 3 in Table 12 are the main expected use cases of the parametric model and the very reasons of launching this project. They correspond to the user expectations identified in Subsection 4.1.1. Thus, PEEC would be well positioned to help provide a response to the 11 customer requests collected.

Use case 4 is more a consequence of the development of PEEC. By gathering and formalizing internal models and practices, this project has helped improving access to environmental information both internally and externally. It makes more easily available to other parts of the company data previously difficult to get (e.g. valuable metals in products, relative contribution of the use of electricity in the total estimated emissions). At this stage, PEEC has not been made directly accessible to the public, but all the assumptions and data used are disclosed in this report and screenshots are given in Appendix B: Screenshots of PEEC. Researchers interested in the tool can contact Ericsson Sustainability Research.

Use case 5 was not the primary purpose but it proved to be of interest when discussing with stakeholders during the development of the tool. As for the parametric model for carbon footprint of cranes [27] intending to provide environmental information for design teams at early stage of product development, PEEC could be used to make comparison between different design or procurement choices. Beware however, it has not been studied to what extend such comparisons are valid.

Finally, PEEC has the potential to contribute to the overall environmental assessment of the telecommunication sector (use case 6), provided that it is maintained and regularly updated. This master's thesis has the advantage of having engaged discussion on the matter inside the company.

5 Discussion

The embodied emissions calculator developed in this thesis is a handy tool enabling quick carbon footprint assessments. Nevertheless, simplified methods always come with drawbacks. We examine in this chapter the validity and limitations of our work.

5.1 Validity of the model

As mentioned in the Methods, the validity of the model is discussed by applying different approaches including an uncertainty screening, a sensitivity analysis, a comparison with the state-of-the-art and a comparison with standards.

5.1.1 Discussions about source of uncertainties

Trying to quantify the environmental impact of an industrial product is by essence a very intricate task. Standardized methods like LCA attempt to reduce and frame uncertainties, but they inevitably add up in the final result. The LCA for ICT standard [14] classify them in three categories: *parameter uncertainties* related to the data used and how close it is from the reality, *scenario uncertainties* regarding the assumptions in the model and *model uncertainties* related to the model itself and its scope. Model uncertainties are dealt with next section (Section 5.2) where we discuss the limitation of our approach in a more general level.

In this subsection, we adopt a systematic approach by going through our model (following the same structure as in the model description Section 4.3) and discussing the first two categories of uncertainties. As we are unable to quantify them, we do our best to provide an indication of their severity in terms of degree of uncertainty and how significant is the part of the embodied footprint they concern. We use a three-level scale that should be understood as follows. For the degree of uncertainty: 'low' is typically less than 15% variation, 'medium', less than 50% whereas 'high' could be more than 50%. For the share of emissions concerned, 'low' means that the uncertainty would affect typically less than 10% of the final result for the embodied emissions, 'medium', less than 25% and 'high' from 25% to the whole result.

In this discussion, no distinction is made between the uncertainties arising specifically from the usage of the tool and the ones inherited from the original LCA data. The reader should also bear in mind that embodied emissions represent a limited part of the entire life cycle footprint for network equipment.

5.1.1.1 Raw material phase

Material declarations. A first source of uncertainties arises from the bill of materials from which the product composition is derived. Products can have different configurations, different suppliers for the same component and they evolve as revisions are made. As a result, specific configuration or revision are picked and averages are done among the suppliers. Moreover, it is not rare that material compositions contain data gaps or overestimates.
-> Degree of uncertainty: low -> Impact on the results: high

Classification into a short list. There can be misclassifications of the substances from the material declarations into the categories in the short list. Additionally, some substances (e.g. aluminum, nickel, chromium) can be present in different types of alloys that have different supply chains and a fortiori different environmental impacts, but they are grouped per atom category. Some categories (namely 'Iron/steel', 'Plastics' and 'Paper/wood') are very

inclusive and may group together substances with very different environmental impact. The impact on the results is probably limited because the main substances have been identified.
-> Degree of approximation: medium -> Share of emissions concerned: low

Extrapolation of unclassified materials. As explained in Part 4.4.1.1, unknown materials (labelled 'other ingredients' or similar in the material declarations), trade secret materials or materials that were not matching any of the category in the short list are linearly extrapolated. This is a strong assumption equivalent to assuming that the unknown composition and the known composition are the same. In the case of trade secret materials, this is likely an underestimation because these materials are probably valuable materials. It is more unclear for the two other categories. Table 13 below displays the amount of materials that could not be classified in the hardware compositions used in this study. Because the ratio of unclassified materials is relatively low, the impact on the results is expected to be limited.
-> Degree of uncertainty: high -> Share of emissions concerned: low

Table 13: **Ratio of materials that couldn't be classified** (in percent of the total mass) in the hardware considered**.**

	Indoor cabinet	RU mech	RU elec	DU mech	DU elec	Fan 6102	PSU	PDU	Power cable
Other ingredients	0,8%	5,6%	4,5%	0,2%	7,8%	0,0%	0,4%	0,0%	0,00%
Trade secret	2,8%	0,4%	4,8%	0,1%	8,8%	0,0%	1,4%	3,6%	17,86%
Not modelled	5,3%	0,9%	4,0%	0,0%	2,3%	0,9%	5,5%	8,2%	0,10%
TOTAL	**9,0%**	**6,9%**	**13,3%**	**0,3%**	**18,9%**	**0,9%**	**7,3%**	**11,8%**	**18%**

Input factors. We remind that the input factors are there to capture the extra quantity of materials needed in entry and lost during the production processes. They have a direct impact on the carbon footprint result as doubling one input factor will double the impact from its corresponding material. Nonetheless, they are expert estimates based on discussions with suppliers that we consider to be of good quality and rather conservative.
-> Degree of uncertainty: medium -> Share of emissions concerned: high

Choice of dataset entry. For the sake of consistency, ecoinvent "market data" have been used (only exception: the 'Plastics' category). Very inclusive in terms of life cycle stages, this dataset has relatively high climate change results compared to others (which makes it a rather conservative choice). Most of time, there was only one corresponding dataset entry to choose from in the database. But in some cases, however ('Iron/Steel', 'Aluminum', 'Silicon', 'Epoxy Resin' and 'Paper/wood' categories), we had to make a choice. Life cycle impact assessment data can differ a lot depending on the dataset entry chosen and more generally on the database.
-> Degree of uncertainty: high -> Share of emissions concerned: high

Uncertainties in databases. Ecoinvent "market data" uses market shares to take into account the reality of global supply chains, that would need to be adapted to the time of the study. More generally, life cycle impact assessment databases always contain uncertainties. They are however reported and reviewed as transparently as possible in a database as commonly used as ecoinvent.
-> Degree of uncertainty: medium -> Share of emissions concerned: high

Applicability to similar products. The idea of PEEC is to be able to reuse previous studies on representative products to get an estimation of the carbon footprint of similar products. In

that case, the user should be very careful as it is difficult to tell to what extent material decompositions of similar product are themselves similar. This can lead to serious over- or underestimations.
-> Degree of approximation: high -> Share of emissions concerned: high

5.1.1.2 Production phase

Component categories. The whole production model is based on the approximation that the module's components can be split into six component categories, each with a model for production carbon footprint. This way for example, production of screws and production of steel frames are considered together in the category "Mechanical components". Additionally, models for production are scaled by reference unit of component (mass for mechanicals, area for printed boards and integrated circuits…) which is also another approximation. These categories and scaling practices are however recognized in the standards and literature in the field.
-> Degree of approximation: medium -> Share of emissions concerned: high

Measuring the hardware characteristics. Obtaining hardware characteristics information can be challenging and error prone. Especially, area of integrated circuits die is hard to measure. Nonetheless, we estimate that researchers can get precise enough information from technical descriptions or product teardowns. This is probably not the biggest source of uncertainties.
-> Degree of uncertainty: low -> Share of emissions concerned: high

Declaration from suppliers. Data on production processes in the datasets used in this thesis (and probably future versions of the tool) come from supplier questionnaires. There is a risk of omission or limited access to environmental information. Moreover, it has not been investigated to what extend the selected supplier is representative for the production of a given part. Production methods and the resulting impact are likely to vary.
-> Degree of uncertainty: medium -> Share of emissions concerned: high

GaBi modelling. As previously for environmental data on raw materials, the resulting emission factor for each production process depends on the modelling choices in the LCA software GaBi. Choices were made in previous work [42] to transform data from questionnaires to GaBi flows. The closest dataset entries had to be selected. It can lead to large differences in particular for electricity mixes that represent a large part of the calculated footprint of production processes (more than 60% and often more than 90%, see right column in Table 6).
-> Degree of uncertainty: high -> Share of emissions concerned: high

5.1.1.3 Packaging

The model for packaging in PEEC, based on an average packaging composition and factors to estimate the mass of packaging for each component category is rather approximative. We did not consider different packaging compositions depending on the component category nor did we update the packaging factors. Nevertheless, given the neglectable impact of packaging in the whole product life cycle, we consider these approximations acceptable.
-> Degree of approximation: medium -> Share of emissions concerned: low

5.1.1.4 Transport

Transport of raw material. The transport of materials from the mines to refineries then to suppliers is not modelled directly in PEEC. It is taken into account in ecoinvent material datasets though, and thus embedded in the material impact factors. The allocation by ecoinvent is based on the geographic situation of the main suppliers for a given material and the one of an average 'global' buyer. We could not report this transport part separately in the results but estimate satisfying that it is somehow taken into account, giving the complexity of the task.
-> Degree of approximation: medium -> Share of emissions concerned: low

Inbound transports. We remind the reader that PEEC allows two allocation methods for inbound transport (from suppliers to assembly).

The **method with distances** is to be preferred provided that the user have data on the location of suppliers and assembly factories and on the modes of transport. This is however very challenging because of the size and complexity of the supply chains. For example, the distance data used in this study and presented in Table 8 has large uncertainties. On top of considering only the location of some suppliers (the representative suppliers asked for production data), the distances are averaged by relative share of assembly factories. It leads to fictive distances that are not representative of the reality of Ericsson logistics chains.
-> Degree of approximation: low (if precise locations) / high (with averages in this study)
-> Share of emissions concerned: low

On the other hand, the **top-down approach based on annually reported transport figures** somehow captures the actual logistics chain and transport flows. An allocation per final mass of module is not ideal, as one kilogram of electronics is not packaged and shipped in the same conditions as one kilogram of cabinet frame, but this remains a reasonable approximation. The method also requires an upstream effort to collect accurate data, and this effort has just started. The recent study of Ericsson inbound transport [49] acknowledges large data gaps in the transport data sets currently available and recommends better data collection efforts in the future. To sum up, for a given module, this general method is likely to give a result very far from the reality of its specific supply chains.
-> Degree of approximation: high -> Share of emissions concerned: low

For **outbound transport** the two allocation methods are also proposed, and the same remarks apply. We recommend the user to use the distance method and precisely estimate the distance travelled by the shipped module from the assembly factory to its final destination when possible to limit uncertainties.

5.1.1.5 Assembly and ICT manufacturer support operations

Top-down allocation approach. An allocation per kilogram of product have been chosen for both assembly and support operations. This is difficult to avoid for support operations, because precisely identifying which amount of R&D, office heating or business travel to attribute to a specific module is almost impossible. However, a more relevant scaling unit could have been selected. Monetary value for example seems more likely to scale with the amount of upstream work required for a module, but price is a more sensible data and is also affected by factors independent of the carbon footprint - like market prices.
For assembly, the same comment applies. Considering the assembly of one kilogram of mechanical frames in the same way as the mounting of one kilogram of electronics on the printed board is a very rough approximation. In this case, specific environmental data could have been obtained on each specific assembly process. All the more so as most of these

processes are carried out within Ericsson's factory. This improvement is suggested for Future work.
-> Degree of approximation: high -> Share of emissions concerned: medium

Figure for yearly mass of products shipped. The total mass of products shipped to customers every year is of poor data quality. It probably contains data gaps and includes some site materials shipped along with the product. A better data collection effort should be made to reduce uncertainties.
-> Degree of uncertainties: high -> Share of emissions concerned: medium

Figures for assembly. Carbon footprint of Ericsson factories (internally reported), carbon footprint of outsourced factories (estimations based on company reporting) and the total weight of products are not very transparent and thus judged to be of rather poor quality.
-> Degree of approximation: medium -> Share of emissions concerned: medium

Figures for support operations. An allocation scenario of 50% of "Ericsson Facilities, Travel and Commuting" is assumed. This is based on expert opinion and could of course be discussed, but never avoided.
-> Degree of approximation: medium -> Share of emissions concerned: medium

5.1.2 Sensitivity analysis

To better understand the impact one specific assumption in our model can have on the results, a sensitivity analysis is performed on the example case of RBS 6000. Different scenarios are formulated in Table 14 and the total carbon footprint result is compared to the baseline in Figure 10.

Table 14: **Scenarios for sensitivity analysis**

Modified parameter	Description	Motivation
Plastics impact factor	Doubled (from 2,5 to 5)	The figure used for plastics is an estimation. We try a more conservative assumption.
Aluminum impact factor	Halved (from 19 to 9,5)	Aluminum emission factor is an influent parameter for telecom products. A lower figure depicts a mix of virgin and recycled aluminum supply.
Gold impact factor	Halved (from 49400 to 24700)	Gold has a very high impact that tends to overwhelm the other materials in the result. We try a lower value (like in other databases).
Raw material input factors	Input waste for all raw materials is doubled (an input factor of 1,1 becomes 1,2)	The extra materials needed as input and wasted during production is estimated in the model. We try a more conservative assumption.
IC emission factor	Doubled (from 1,72 to 3,44)	IC is identified in most LCA for ICT studies as a major contributor. In addition, the figure used in the example is rather low compared to other studies.
Assembly emission factor	Doubled	Assembly is very roughly taken into account. We try a more conservative assumption.

Scenario for support operation	A 75% allocation of overall Ericsson operations is assumed instead of 50%	Allocating support operations to a product is challenging. We try a more conservative assumption.

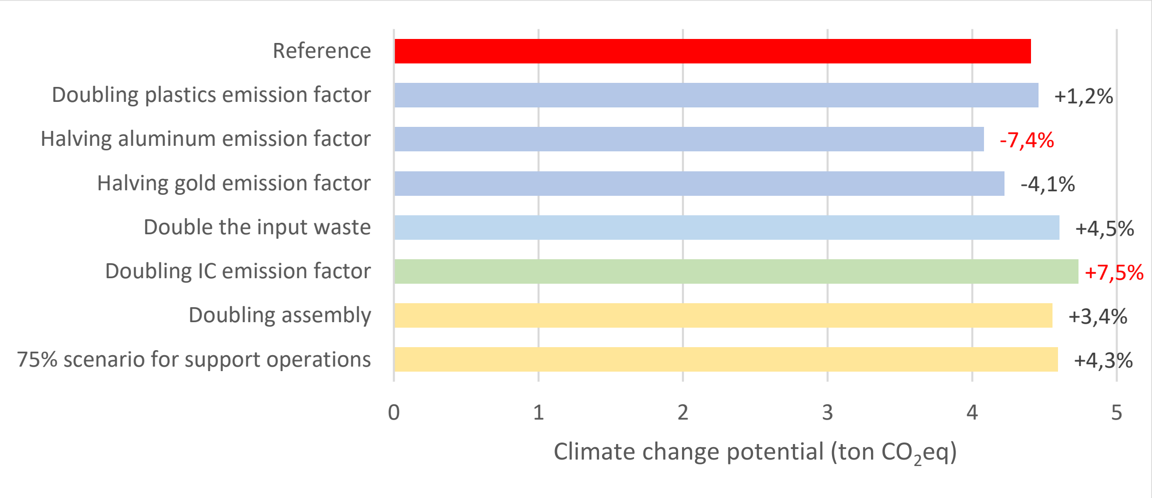

Figure 10: **Sensitivity analysis results.** The different scenarios are simulated with PEEC and compared to the reference results for RBS 6000 (presented in 4.5). The percentages indicate the deviation from the reference.

Overall, this analysis tests the sensitivity of very few parameters compared to the hundreds of assumptions and data points in PEEC. However, we believe that it captures the most important or uncertain parameters. Except maybe for the plastics emission factor, **every alternative scenario studied has a rather high impact on the results**. In fact, even if the deviation is always lower than 8%, it must be reminded that it is caused only by one parameter and on the full life cycle.

Aluminum extraction alone is responsible of 14,8% of the total embodied emissions of RBS 6000 and this figure is of 8,2% for gold. Consequently, uncertainties on the mass of these two materials in the product compositions or uncertainties on their emission factors have a high impact on the results. This confirms our choice to bring forward in PEEC these two emission factors for more easy modification by the user (see Subsection 4.2.2).

Not surprisingly, data on integrated circuits is also identified as sensitive in the results. Even if telecom products have rather large frames compared to other ICT products like smartphones or personal computers, the production of IC dies alone still makes up for 7,5% of the total footprint here. It highlights the importance of collecting precise and high-quality data for this component.

In conclusion, the sensitivity analysis warns us about the repercussions of overestimating or underestimating one crucial parameter. One more time, the user of PEEC should be careful about the quality of data used as input and his or her usage of the results. Hopefully in our case, the embodied emissions are relatively well distributed through the life cycle, which prevents us from having one parameter responsible for more than half of the results.

5.1.3 Comparison with literature

In the Background (Section 2.3), other parametric models from the literature for ICT and non ICT products were analyzed. How does PEEC compares with the state-of-the-art?

PEEC asks the user for 11 hardware parameters (mass of mechanics, area of PWB, etc. listed in Table 2). Additionally, emission factors have to be filled in or at least selected from lists of predefined values. This is very similar to the parametric model for cranes [27] also assessing a carbon footprint thanks to 13 primary parameters and optional secondary parameters. For the latter, the authors claim to obtain less than 4% deviation between primary-only and complete assessment (close to full LCA) on six case studies. We did not run such a validation, but if carefully tuned with updated data, PEEC can support a standard compliant LCA.

Given the low number of LCA results for telecommunication equipment, a scientific method like regression or correlation analysis couldn’t be performed as in [28], [29] or [30] to identify the most impactful parameters. It is regrettable, but a streamlined tool such as PEEC could potentially help running experiments and testing parameters in the future. One should not forget that PEEC is bound to evolve over time. Besides, compared to these three studies, PEEC doesn't just give a simplified formula based on a few parameters but a stand-alone, transparent, and flexible framework for carbon footprinting.

To finish, let’s compare PEEC with the two closest tools in the literature for carbon footprint of ICT products: PAIA [30] and Eco-impact Estimator [33]. Firstly, it should be reminded that both these tools are not in open access, but either sold or accessible through membership. Both of them benefit from around 10 years of development. They started off as spreadsheets before eventually becoming web based. They allow the carbon footprint estimation of a large variety of ICT devices over their full life cycle, although none of them include telecommunication network equipment to the best of our knowledge. Eco-impact Estimator has an assessment method close to PEEC’s, dividing the device into component categories. A gap of less than 10-15% compared to detailed LCA is claimed [34], without more disclosure on the validation method. On the other hand, PAIA, as already explained, has a different approach. Uncertainties are quantified and put in the center of the assessment method. It is PAIA that is for example behind the product carbon footprints published in Dell’s website [9] and that explains why the results are disclosed with such a wide uncertainty margin.

All in all, we believe that our work brings a valuable contribution to the emerging field of ICT environmental assessment by transparently publishing a method for embodied emission estimation of telecommunication equipment.

5.1.4 Compliance with standards

Let us recall that the purpose of the tool developed in this master’s thesis is to provide a simplified way to estimate the embodied emissions of network equipment and not to perform a complete LCA. If a full LCA were to be carried out with the help of the tool, it would be up to the user to ensure and report compliance with the standards. However, the recommendations from the joint LCA standard by ITU/ETSI [14], [15] were considered as much as possible during the development of the tool. In particular, the fundamental LCA principles of relevance, completeness, consistency, accuracy and transparency have guided this work.

The Results chapter in this report presents in a transparent way the scope, assumptions (approximations, allocations and cut-offs) and data collection principles of the model. It does not target all the life cycle stages required for an LCA (see the system boundaries in Figure

2). Table 15 below summarizes the main simplifications made for each life cycle stage and the main deviation from the standard's requirements.

Table 15: **PEEC modelling assumptions and comparison with standards.**

Life cycle stage	Main simplifications	Deviation from standard [14]
Raw material	• Sorting materials into a short list of materials • If using default values: assuming similar material composition for similar products • Use of Life Cycle Inventory databases	• Do not consider all the materials in the minimal list of raw material (Annex H)
Part production	• Use of secondary data allocated per weight	• Transport not included in this stage but treated apart • No special handling of software as a product part though somehow accounted for in the support operations
Packaging	• Packaging weight estimated as a fraction of the part weight • Same packaging composition used for all parts	• Production and assembly of packaging not taken into account
Transport	• Transport of raw material included to an unknown extend in the raw material figure • Top-down allocation approach based on annual figures • Distance method based on average distances	• The distance method should be preferred, with real travelled distances
Assembly	• Top-down allocation approach based on annual figures	• No precise data collection for assembly processes
Support operations	• Top-down allocation approach based on annual figures	• Support activities considered only for Ericsson and not for its suppliers
General comments	• PEEC simplifies the use of secondary data which has to be avoided as much as possible according to the standard as it necessarily leads to poor geographical representativeness, data age and technological correlation • No external review other than the examination of this master's thesis has been performed • ReCiPe Midpoint (H) is used as a climate change indicator throughout this study, and not the global warming characterization from IPCC as recommended in the standard	

5.2 Limitations

On a general level, our work presents a number of limitations that we would like to inform the reader about in this section.

The first criticism concerns the scope of the parametric model developed. PEEC is restricted to only one environmental impact indicator - climate change potential - through the estimation of greenhouse gas emissions. Even if global warming is widely discussed, reported upon and recognized as one of the most important environmental issue [50], other issues such as resource depletion, human toxicity or water pollution should be considered. The LCA standards require the selection of a comprehensive set of environmental issues related to the product system being studied [13] and it has been shown that no impact indicator alone was representative of the others [21].

In addition, PEEC excludes from its scope the use phase and end-of-life of the products. The use phase is the most impactful life cycle stage in telecommunication network products [51] because of their long life span and intense utilization. The motivation is though that operators have better ways to calculate operational energy consumption than approximations based on rough assumptions on lifetime and average power consumption. However, emissions related to end-of-life treatment are sometimes considered as “embodied emissions” because they are also only related to hardware. Such an inclusion would have increased the comprehensiveness of PEEC.

Another criticism of the model concerns its transparency and universality. PEEC has been developed in close link with the company Ericsson. Even if it could be adapted to others, it now focuses on Ericsson products and uses the company’s data and previous models. Because of non-disclosure agreements, some references in this thesis are kept confidential. They have been reduced to a minimum and an old generation of products was used as the reference to be able to remain as transparent as possible on potentially business sensitive figures (i.e. area of electronic products, localization of suppliers, mass of product sold).

Regarding the methods, no rigorous identification of impactful parameters or validation of the model could be carried out. This is due to the current lack of environmental data for telecommunication networks in the field. Besides, a more systematic collection and analysis of customer requests could have been performed. Similarly, the usability study in this thesis is very limited and could have been improved. For example, by having a quantitative analysis with more respondents and a wider variety of profile or comparison of design choices.

Lastly, we will never insist enough on the necessity to be very careful with the use of PEEC and the communication of its results. The Excel tool is easy to use, but it will be to the responsibility of the user to ensure that its versions are up to date and its assumptions stay reasonable to avoid the spread of sourceless and poor-quality data. The results should always be shared along with an appropriate disclaimer and details around assumptions and the sources of data used.

6 Future work

This master's thesis has achieved what we claim to be a consistent and coherent work. An outcome of this project is a first version of PEEC. Let us recall that the primary objective of the work was the model and implementation rather than the data, and the current data should be considered as proxy figures. Also, the tool is bound to evolve. In this section we give ideas and recommendations for future enhancement.

i. To better reflect the current generation of network equipment, efforts should be put into **gathering new data on the latest products**. This can be achieved by obtaining material declarations of reference products and entering them in PEEC according to the method described in this report. Some annual figures like assembly, transport or support operations should be kept up to date. In parallel, the last questionnaire to suppliers for data on manufacturing processes dates from 2014. The supply chain, processes and use of green sources are very likely to have changed. Moreover, it is reasonable to assume that suppliers are better able to provide quality environmental data today than some years ago.

ii. We would recommend **refining the model for assembly**. Indeed, as mentioned in the Discussion, the current top-down approach leads to large approximations that could be avoided by collecting specific data on assembly processes.

iii. Future versions of the tool would benefit from including **more environmental impact indicators**. While little work would be required for some part of the life cycle (i.e. the raw material phase, because material databases already include data on other environmental harms), it would demand a considerable effort for some others.

iv. Similarly, the scope of the tool could be extended, by **including recycling and end-of-life** in the model. This would increase the comprehensiveness of PEEC. However, these activities are usually beyond the control of Ericsson, unless for production waste.

v. Future work is also needed to **study the adoption of the tool** in the company and the industry, to investigate its usability and relevance to customer requests.

vi. In parallel, an **experimental validation study** when the tool is updated with more recent data would increase the robustness and scientific credibility of the work.

vii. Finally, it should be noted that both the current approaches (naming PAIA and Eco Impact Estimator, see Background or Comparison with literature) have started as spreadsheets before moving to a hosted and ported environment. MS Excel has the advantage of being flexible and widespread, but a workbook such as PEEC is likely to break or allow unintended modifications. A **later implementation as a web-based tool could be imagined**.

viii. Alternatively, we would recommend **considering collaboration with PAIA or Eco Impact Estimator**. Both initiatives are calling for contribution and they benefit from 10 years of improvement with many partners. We think that the work presented in this thesis could be valuable to help developing any of these tools for mobile network equipment.

7 Conclusion

In this master's thesis report, we present PEEC, a parametric model to estimate embodied carbon emissions of telecommunication networks. Our initial ambition was to develop a tool fostering and simplifying the access to environmental data in the industry while remaining anchored to a strong Life Cycle Assessment (LCA) methodology. We built upon previous studies and models for telecom equipment, inputs from an LCA expert and workshops and discussion with people in the industry. The standards for LCA in the ICT sector were considered, as well as recent literature on the topic. Stakeholder expectations were identified from the beginning and usability of the tool had occupied a central place throughout the building process.

Overall and given the scope and resources for this project, we consider that it has successfully achieved the ambitions set at the outset. PEEC balances the trade-off between scientific rigor and practical usability by allowing carbon footprint estimations at different levels of abstraction and thus for different types of users. A precise description of the model is given, providing transparency on calculation methods and assumptions. The tool has also been tested on the example of the previous generation of Ericsson radio base station (RBS 6000). Expected use cases are described to explain how PEEC can support the sustainability work in the industry. On top of all, we have endeavored to provide a systematic discussion about the assumptions and limitations in the model. We performed a sensitivity analysis and compared our model with the standards and the state-of-the-art.

In the bigger picture, we sincerely hope that this kind of work can help us all, consumers of ICT devices, to realize the environmental impacts hidden behind our screens. The question raised in the introduction whether 5G will enable the emergence of more sustainable practices or rather clutter up the network with a multitude of pointless new uses remains open. It is not an easy question, but we do believe that citizens, organizations and governments, if empowered with reliable information – in this case regarding the embodied part of the footprint of networks – could have the means to actively tilt the uses of new technologies in the right direction.

This master's thesis is our contribution to the great and necessary ecological transition of society.

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[51] J. Malmodin, D. Lundén, Å. Moberg, G. Andersson, and M. Nilsson, "Life Cycle Assessment of ICT: Carbon Footprint and Operational Electricity Use from the Operator, National, and Subscriber Perspective in Sweden," *Journal of Industrial Ecology*, vol. 18, no. 6, pp. 829–845, Dec. 2014, doi: 10.1111/jiec.12145.

Appendix A: GaBi carbon emission data for PWB and IC

In this appendix, linear regressions on greenhouse gas emission data available in the Life Cycle Assessment (LCA) software GaBi for Integrated Circuits (ICs) and Printed Wiring Boards (PWBs) are presented.

It reflects a quick study that has been performed by the author to contextualize the data currently used in PEEC and obtained from Ericsson suppliers.

Brief description of the data

GaBi databases [43] contain models for electronics (under Processes>Production> Electronics>Components general). In particular, they have:

- 21 data points for PWBs with various number of layers and different surface finishes. According to the documentation[9], they are **average cradle-to-gate data per square meter of PWB**, actualized for the period 2019-2022 on a data collection from 2000-2011.
- 35 data points for ICs (later called "Dataset2") for different sizes and technologies. They are also **cradle-to-gate data per IC**, actualized for the period 2019-2022 on a data collection from 2004-2014.
- 12 other data points for ICs ("Dataset1") for different sizes and technologies. They are also **cradle-to-gate data per IC**, actualized for the period 2019-2022. No date was found for the data collection period.

Plot of the data[10]

Global warming potential results (using ReCiPe Midpoint (H) climate change indicator) for the 21 dataset entries for PWBs are plotted in Figure 11.

For ICs, different scaling units have been tried: the mass of IC (Figure 12), the area of housing (Figure 13) and the area of die (Figure 14). Mass of IC and dimensions of housing are directly available in the title of each dataset entry, whereas we had to look at the ratio between die area and housing area for each technology of IC in the documentation (only available for Dataset2) to get the area of die.

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[9] The GaBi dataset documentation can be accessed online at this URL: www.gabi-software.com/international/databases/gabi-data-search

[10] For Ericsson readers: the underlying datasheet is available here: https://erilink.ericsson.se/eridoc/erl/objectId/09004cffc68cdc8f?docno=GFTL-21:000210Uen&action=current&format=excel12book

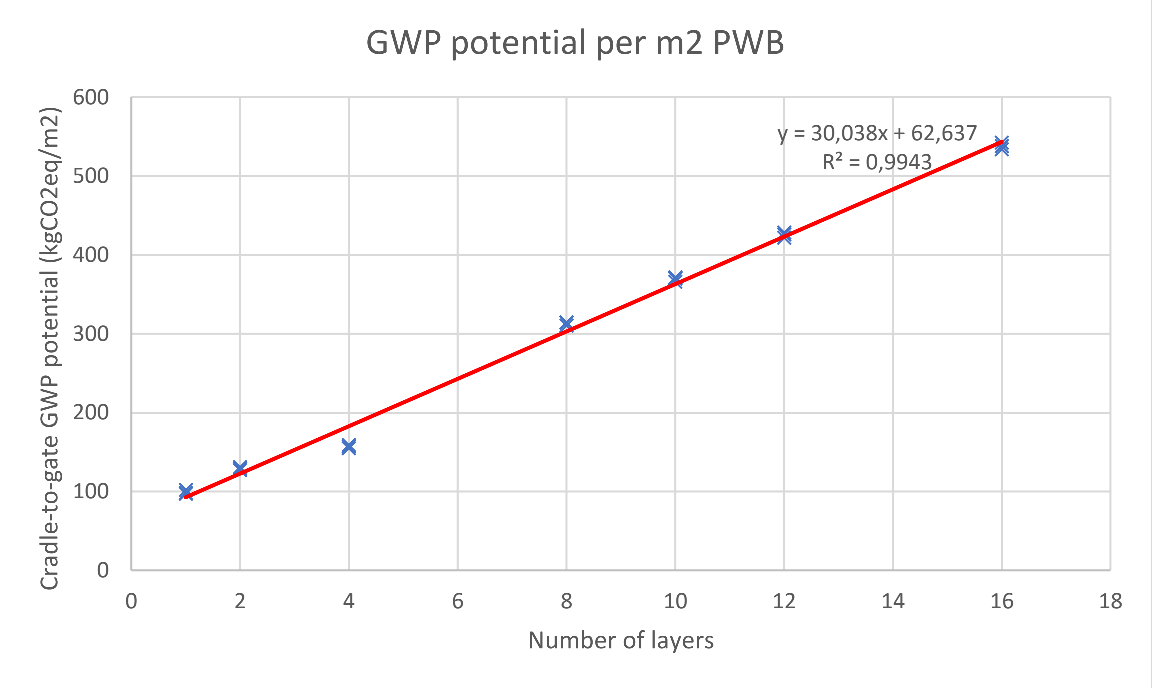


Figure 11: **GaBi cradle-to-gate carbon emission data for PWBs.** The linear regression gives $30 kgCO_2eq/(m^2*layers)$.

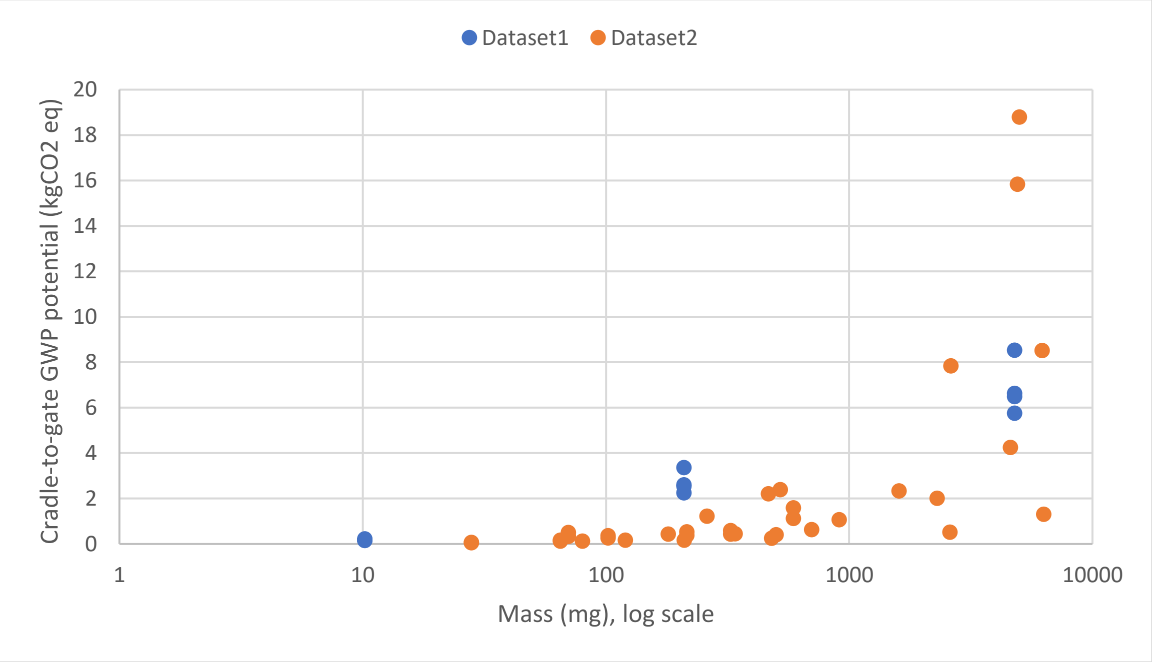


Figure 12: **GaBi cradle-to-gate carbon emission data for ICs per mass of IC package.**

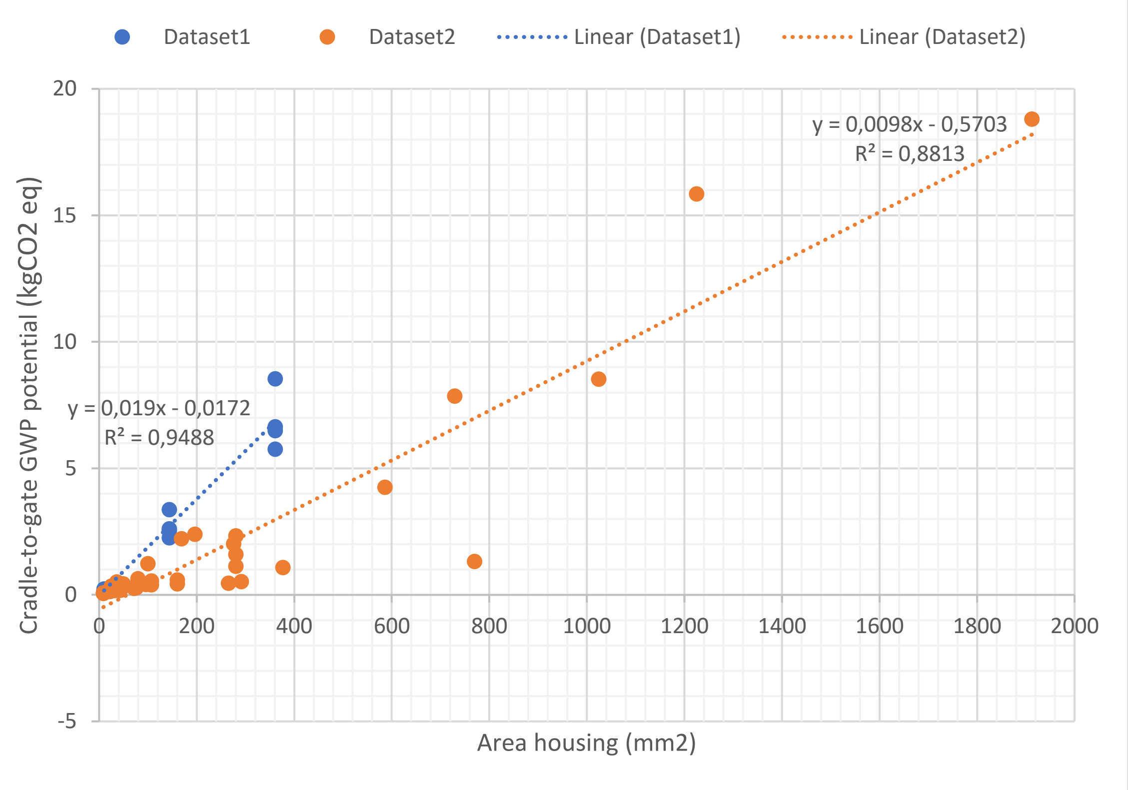


Figure 13: **GaBi cradle-to-gate carbon emission data for ICs per area of IC package.**

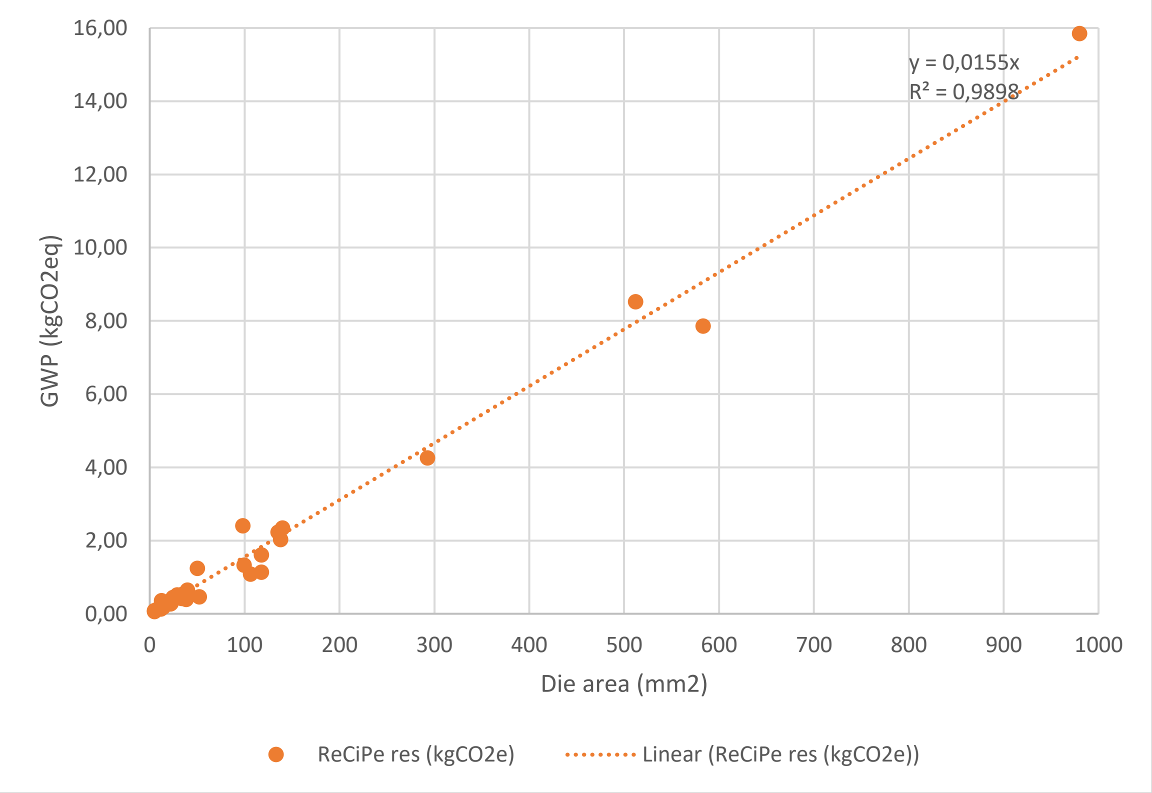


Figure 14: **GaBi cradle-to-gate carbon emission data for ICs per area of IC die.** The linear regression gives 1,55kgCO_2eq/cm^2.

Results and discussion

PWBs. PWB models in GaBi are given per square meter of PWB. When carbon emission results are plotted per number of layers (Figure 11), the data show a strong linear correlation (R^2=0,994). It is probably because the GaBi dataset itself has been created in the first place through some kind of parametric model. Hence the relation between cradle-to-gate emissions of a PWB, with $\boldsymbol{a} = \mathbf{30,0}$ and $b = 62{,}6$ the two coefficients from the linear regression:

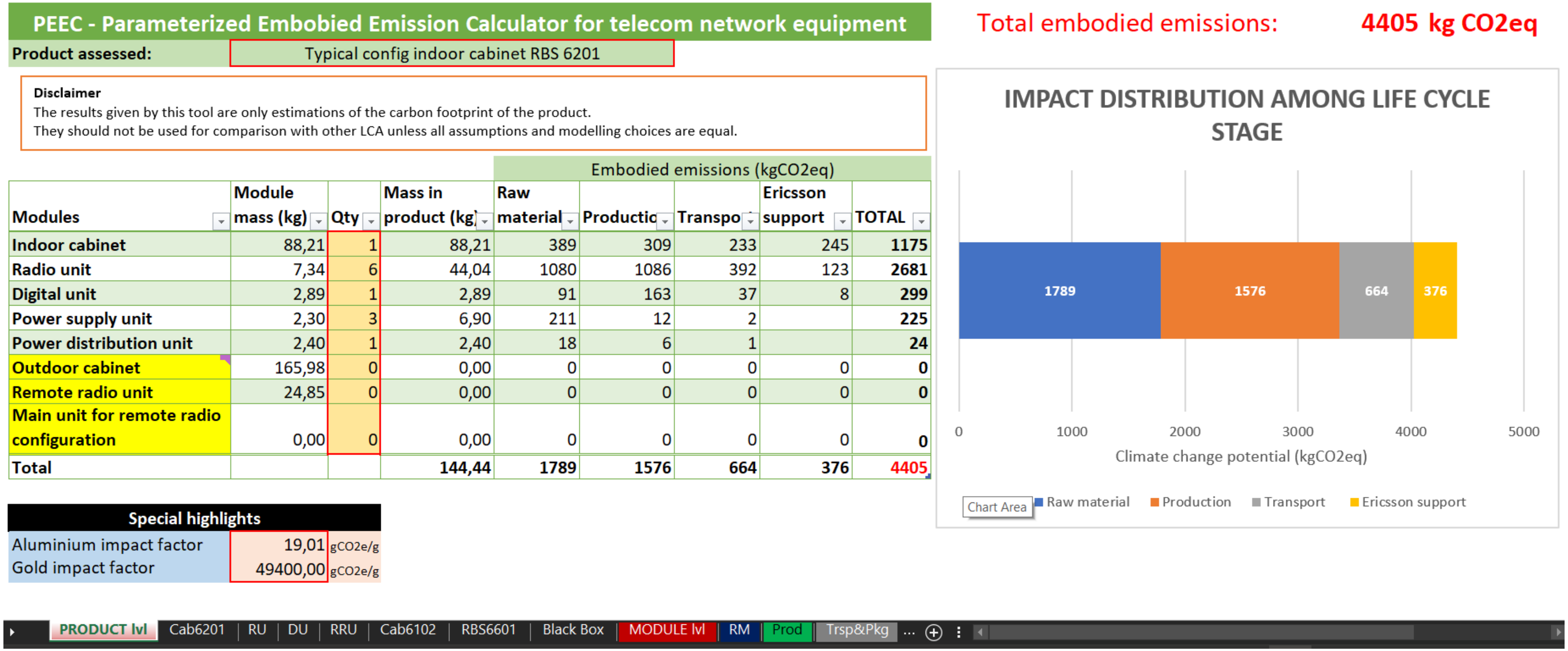
$$emissions_{PWB} = (a. |layers| + b) * area_{PWB}$$

The emission factor currently used in PEEC, for production only, is $\boldsymbol{a} = \mathbf{27,7}$ $kgCO_2/m^2$ (see Table 6). This is coherent with GaBi cradle-to-gate value, but in comparison our model doesn't have an offset.

ICs. Looking at the three plots for IC models in GaBi, it is evident that the best scaling unit is the area of die. As mentioned in 4.3.2.3, this is coherent with the literature and standards. The linear regression in Figure 14 gives a strong correlation and an emission factor of **1,55**$\mathbf{kgCO_2/cm^2}$ **of die**, which is lower than the one we use (**1,72**$\mathbf{kgCO_2/cm^2}$ **of die**), even if it should be more inclusive (cradle-to-gate VS production only). The reason for that has not been investigated.

Appendix B: Screenshots of PEEC

In this appendix are appended screenshots of the most important sheets of PEEC. Researcher interested in the tool may contact Ericsson Sustainability Research (pernilla.bergmark@ericsson.com).



PEEC - Parameterized Embobied Emission Calculator for telecom network equipment

Product assessed: Typical config indoor cabinet RBS 6201

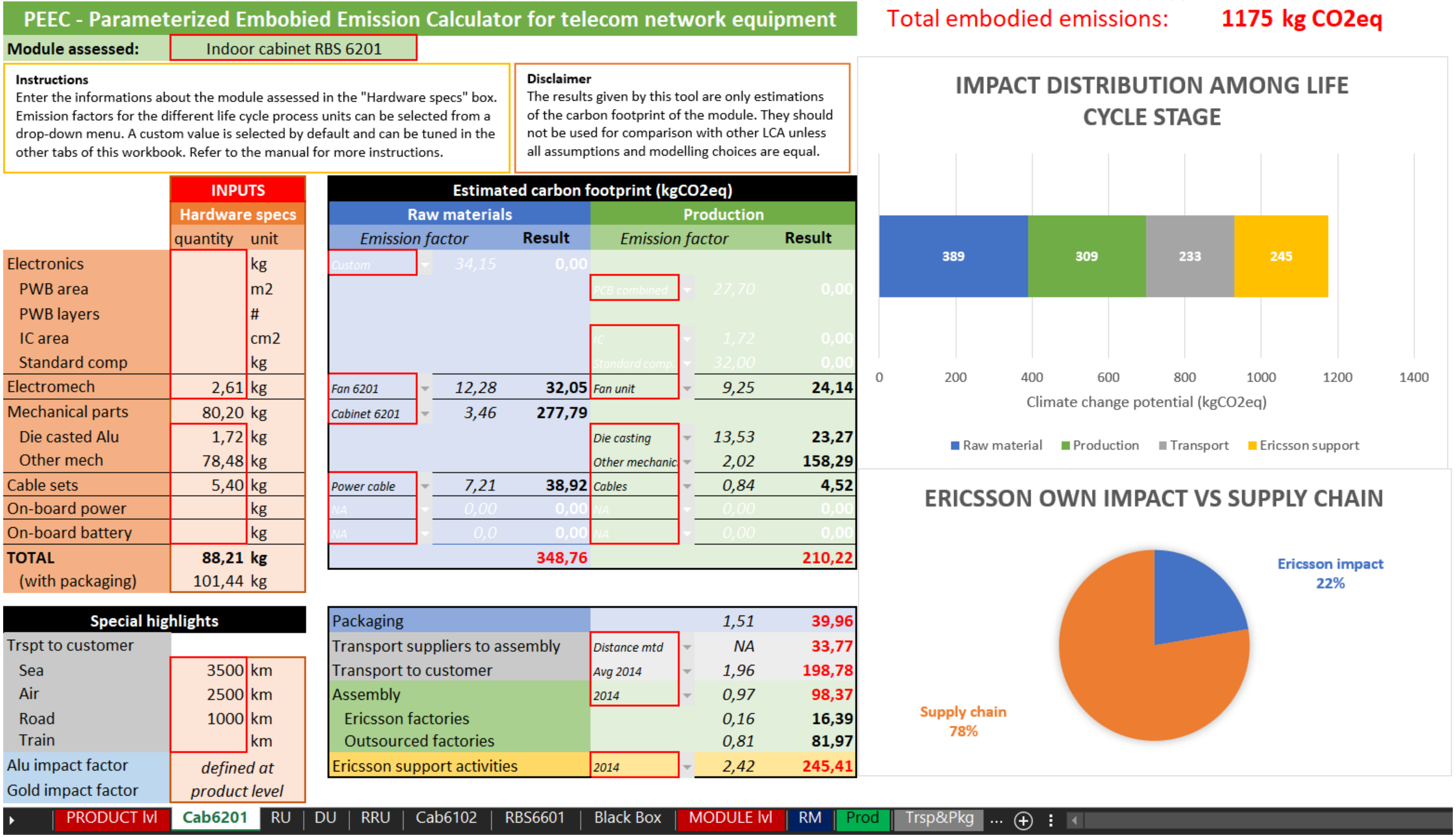
Total embodied emissions: 4405 kg CO2eq

Disclaimer
The results given by this tool are only estimations of the carbon footprint of the product.
They should not be used for comparison with other LCA unless all assumptions and modelling choices are equal.

				Embodied emissions (kgCO2eq)				
Modules	**Module mass (kg)**	**Qty**	**Mass in product (kg)**	**Raw material**	**Productio**	**Transpo**	**Ericsson support**	**TOTAL**
Indoor cabinet	88,21	1	88,21	389	309	233	245	**1175**
Radio unit	7,34	6	44,04	1080	1086	392	123	**2681**
Digital unit	2,89	1	2,89	91	163	37	8	**299**
Power supply unit	2,30	3	6,90	211	12	2		**225**
Power distribution unit	2,40	1	2,40	18	6	1		**24**
Outdoor cabinet	165,98	0	0,00	0	0	0	0	**0**
Remote radio unit	24,85	0	0,00	0	0	0	0	**0**
Main unit for remote radio configuration	0,00	0	0,00	0	0	0	0	**0**
Total			**144,44**	**1789**	**1576**	**664**	**376**	**4405**

Special highlights		
Aluminium impact factor	19,01	gCO2e/g
Gold impact factor	49400,00	gCO2e/g

Figure 15: **PEEC product sheet**, filled in here with the RBS6000 configuration described in Section 4.5. The data for the different modules are fetched in the corresponding module sheets or the "black box" sheet, i.e. the tabs to the right of the "PRODUCT lvl" tab.



PEEC - Parameterized Embobied Emission Calculator for telecom network equipment

Module assessed: Indoor cabinet RBS 6201

Total embodied emissions: **1175 kg CO2eq**

Instructions
Enter the informations about the module assessed in the "Hardware specs" box. Emission factors for the different life cycle process units can be selected from a drop-down menu. A custom value is selected by default and can be tuned in the other tabs of this workbook. Refer to the manual for more instructions.

Disclaimer
The results given by this tool are only estimations of the carbon footprint of the module. They should not be used for comparison with other LCA unless all assumptions and modelling choices are equal.

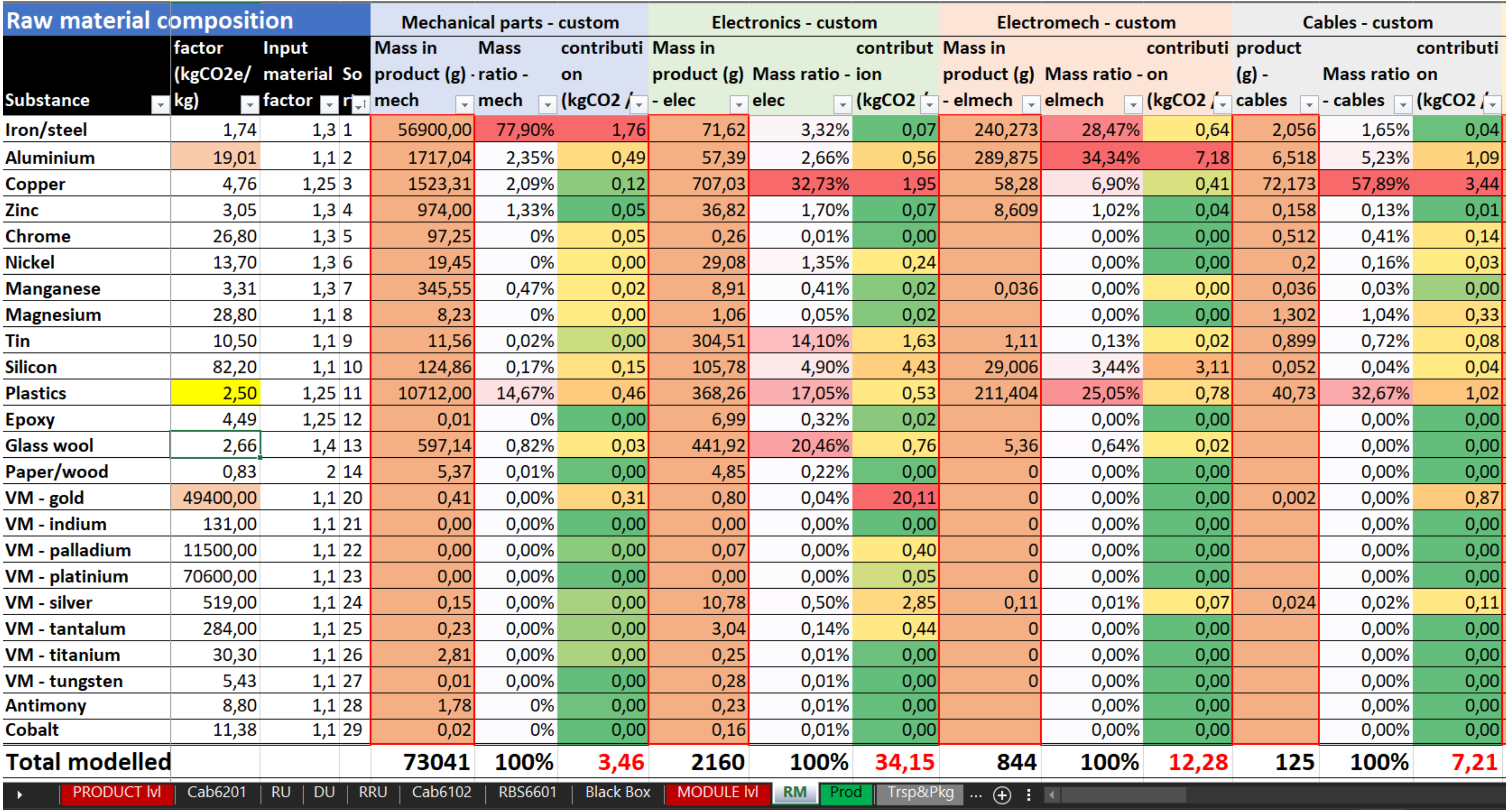
INPUTS / **Estimated carbon footprint (kgCO2eq)**

	Hardware specs		Raw materials			Production		
	quantity	unit	Emission factor		Result	Emission factor		Result
Electronics		kg	Custom	34,15	0,00			
PWB area		m2				PCB combined	27,70	0,00
PWB layers		#						
IC area		cm2				IC	1,72	0,00
Standard comp		kg				Standard comp.	32,00	0,00
Electromech	2,61	kg	Fan 6201	12,28	**32,05**	Fan unit	9,25	**24,14**
Mechanical parts	80,20	kg	Cabinet 6201	3,46	**277,79**			
Die casted Alu	1,72	kg				Die casting	13,53	**23,27**
Other mech	78,48	kg				Other mechanic.	2,02	**158,29**
Cable sets	5,40	kg	Power cable	7,21	**38,92**	Cables	0,84	**4,52**
On-board power		kg	NA	0,00	0,00	NA	0,00	0,00
On-board battery		kg	NA	0,0	0,00	NA	0,00	0,00
TOTAL	**88,21**	**kg**			**348,76**			**210,22**
(with packaging)	101,44	kg						

Special highlights		
Trspt to customer		
Sea	3500	km
Air	2500	km
Road	1000	km
Train		km
Alu impact factor	*defined at*	
Gold impact factor	*product level*	

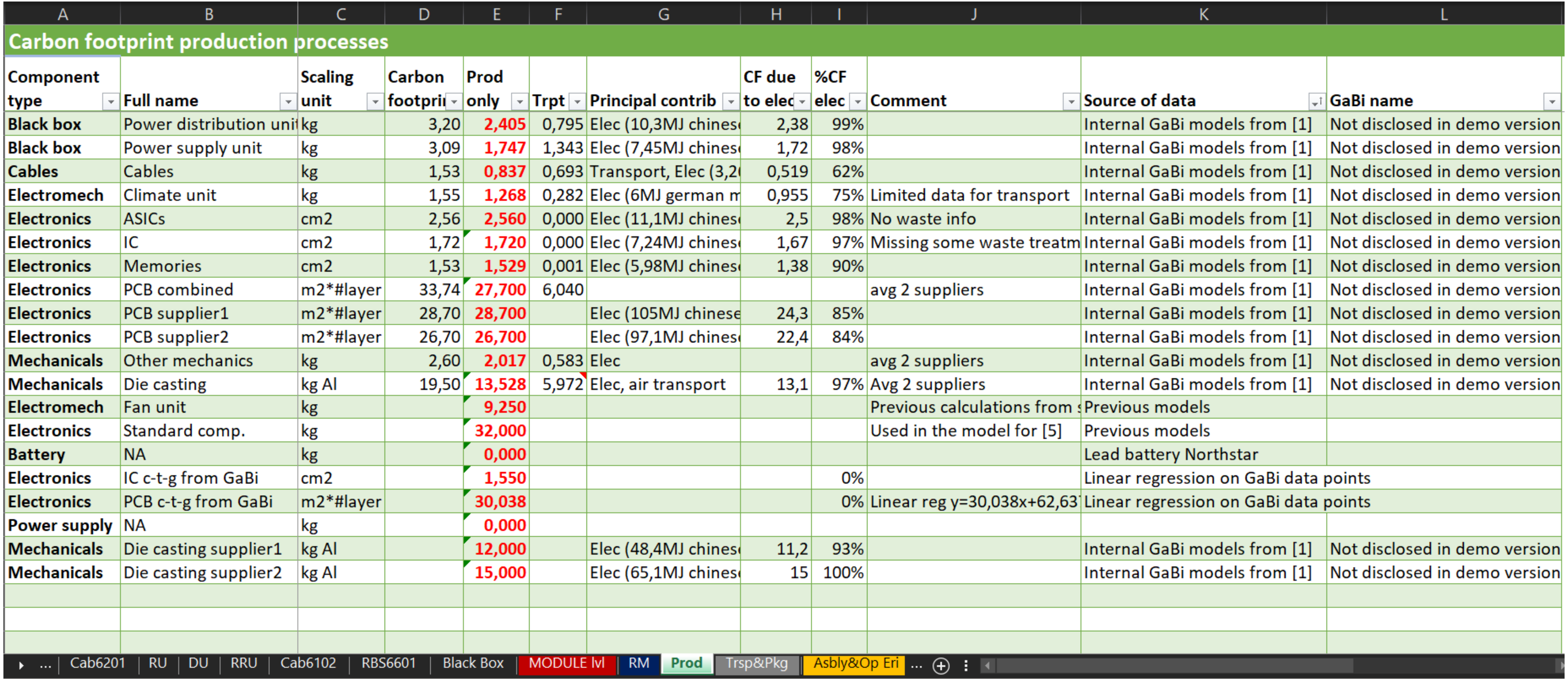
Packaging		1,51	**39,96**
Transport suppliers to assembly	Distance mtd	NA	**33,77**
Transport to customer	Avg 2014	1,96	**198,78**
Assembly	2014	0,97	**98,37**
Ericsson factories		0,16	**16,39**
Outsourced factories		0,81	**81,97**
Ericsson support activities	2014	2,42	**245,41**

Figure 16: **PEEC module sheet** instantiated with data for indoor cabinet, as described in Section 4.5.



Raw material composition				Mechanical parts - custom			Electronics - custom			Electromech - custom			Cables - custom		
Substance	factor (kgCO2e/ kg)	Input material factor	So r	Mass in product (g) - mech	Mass ratio - mech	contributi on (kgCO2 /	Mass in product (g) - elec	Mass ratio - elec	contribut ion (kgCO2	Mass in product (g) - elmech	Mass ratio - elmech	contributi on (kgCO2 /	product (g) - cables	Mass ratio - cables	contributi on (kgCO2 /
Iron/steel	1,74	1,3	1	56900,00	77,90%	1,76	71,62	3,32%	0,07	240,273	28,47%	0,64	2,056	1,65%	0,04
Aluminium	19,01	1,1	2	1717,04	2,35%	0,49	57,39	2,66%	0,56	289,875	34,34%	7,18	6,518	5,23%	1,09
Copper	4,76	1,25	3	1523,31	2,09%	0,12	707,03	32,73%	1,95	58,28	6,90%	0,41	72,173	57,89%	3,44
Zinc	3,05	1,3	4	974,00	1,33%	0,05	36,82	1,70%	0,07	8,609	1,02%	0,04	0,158	0,13%	0,01
Chrome	26,80	1,3	5	97,25	0%	0,05	0,26	0,01%	0,00		0,00%	0,00	0,512	0,41%	0,14
Nickel	13,70	1,3	6	19,45	0%	0,00	29,08	1,35%	0,24		0,00%	0,00	0,2	0,16%	0,03
Manganese	3,31	1,3	7	345,55	0,47%	0,02	8,91	0,41%	0,02	0,036	0,00%	0,00	0,036	0,03%	0,00
Magnesium	28,80	1,1	8	8,23	0%	0,00	1,06	0,05%	0,02		0,00%	0,00	1,302	1,04%	0,33
Tin	10,50	1,1	9	11,56	0,02%	0,00	304,51	14,10%	1,63	1,11	0,13%	0,02	0,899	0,72%	0,08
Silicon	82,20	1,1	10	124,86	0,17%	0,15	105,78	4,90%	4,43	29,006	3,44%	3,11	0,052	0,04%	0,04
Plastics	2,50	1,25	11	10712,00	14,67%	0,46	368,26	17,05%	0,53	211,404	25,05%	0,78	40,73	32,67%	1,02
Epoxy	4,49	1,25	12	0,01	0%	0,00	6,99	0,32%	0,02		0,00%	0,00		0,00%	0,00
Glass wool	2,66	1,4	13	597,14	0,82%	0,03	441,92	20,46%	0,76	5,36	0,64%	0,02		0,00%	0,00
Paper/wood	0,83	2	14	5,37	0,01%	0,00	4,85	0,22%	0,00	0	0,00%	0,00		0,00%	0,00
VM - gold	49400,00	1,1	20	0,41	0,00%	0,31	0,80	0,04%	20,11	0	0,00%	0,00	0,002	0,00%	0,87
VM - indium	131,00	1,1	21	0,00	0,00%	0,00	0,00	0,00%	0,00	0	0,00%	0,00		0,00%	0,00
VM - palladium	11500,00	1,1	22	0,00	0,00%	0,00	0,07	0,00%	0,40	0	0,00%	0,00		0,00%	0,00
VM - platinium	70600,00	1,1	23	0,00	0,00%	0,00	0,00	0,00%	0,05	0	0,00%	0,00		0,00%	0,00
VM - silver	519,00	1,1	24	0,15	0,00%	0,00	10,78	0,50%	2,85	0,11	0,01%	0,07	0,024	0,02%	0,11
VM - tantalum	284,00	1,1	25	0,23	0,00%	0,00	3,04	0,14%	0,44	0	0,00%	0,00		0,00%	0,00
VM - titanium	30,30	1,1	26	2,81	0,00%	0,00	0,25	0,01%	0,00	0	0,00%	0,00		0,00%	0,00
VM - tungsten	5,43	1,1	27	0,01	0,00%	0,00	0,28	0,01%	0,00	0	0,00%	0,00		0,00%	0,00
Antimony	8,80	1,1	28	1,78	0%	0,00	0,23	0,01%	0,00		0,00%	0,00		0,00%	0,00
Cobalt	11,38	1,1	29	0,02	0%	0,00	0,16	0,01%	0,00		0,00%	0,00		0,00%	0,00
Total modelled				**73041**	**100%**	**3,46**	**2160**	**100%**	**34,15**	**844**	**100%**	**12,28**	**125**	**100%**	**7,21**

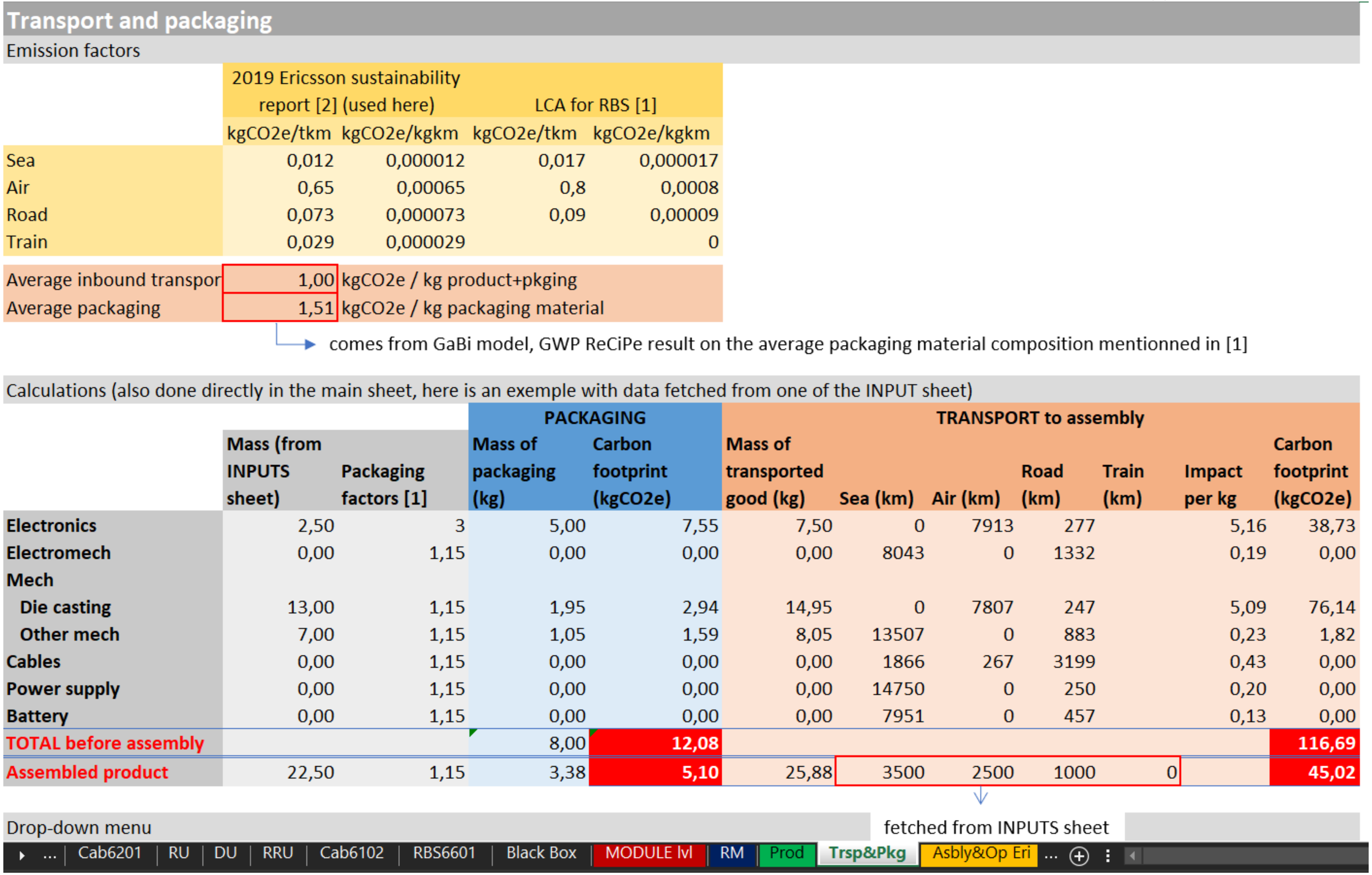
Figure 17: **PEEC raw material sheet.** Background calculations from the modules' material compositions to derive the raw material emission factors, as explained in Subsection 4.4.1.



Carbon footprint production processes

Component type	Full name	Scaling unit	Carbon footpri	Prod only	Trpt	Principal contrib	CF due to elec	%CF elec	Comment	Source of data	GaBi name
Black box	Power distribution unit	kg	3,20	2,405	0,795	Elec (10,3MJ chines	2,38	99%		Internal GaBi models from [1]	Not disclosed in demo version
Black box	Power supply unit	kg	3,09	1,747	1,343	Elec (7,45MJ chines	1,72	98%		Internal GaBi models from [1]	Not disclosed in demo version
Cables	Cables	kg	1,53	0,837	0,693	Transport, Elec (3,2	0,519	62%		Internal GaBi models from [1]	Not disclosed in demo version
Electromech	Climate unit	kg	1,55	1,268	0,282	Elec (6MJ german m	0,955	75%	Limited data for transport	Internal GaBi models from [1]	Not disclosed in demo version
Electronics	ASICs	cm2	2,56	2,560	0,000	Elec (11,1MJ chines	2,5	98%	No waste info	Internal GaBi models from [1]	Not disclosed in demo version
Electronics	IC	cm2	1,72	1,720	0,000	Elec (7,24MJ chines	1,67	97%	Missing some waste treatm	Internal GaBi models from [1]	Not disclosed in demo version
Electronics	Memories	cm2	1,53	1,529	0,001	Elec (5,98MJ chines	1,38	90%		Internal GaBi models from [1]	Not disclosed in demo version
Electronics	PCB combined	m2*#layer	33,74	27,700	6,040				avg 2 suppliers	Internal GaBi models from [1]	Not disclosed in demo version
Electronics	PCB supplier1	m2*#layer	28,70	28,700		Elec (105MJ chinese	24,3	85%		Internal GaBi models from [1]	Not disclosed in demo version
Electronics	PCB supplier2	m2*#layer	26,70	26,700		Elec (97,1MJ chines	22,4	84%		Internal GaBi models from [1]	Not disclosed in demo version
Mechanicals	Other mechanics	kg	2,60	2,017	0,583	Elec			avg 2 suppliers	Internal GaBi models from [1]	Not disclosed in demo version
Mechanicals	Die casting	kg Al	19,50	13,528	5,972	Elec, air transport	13,1	97%	Avg 2 suppliers	Internal GaBi models from [1]	Not disclosed in demo version
Electromech	Fan unit	kg		9,250					Previous calculations from s	Previous models	
Electronics	Standard comp.	kg		32,000					Used in the model for [5]	Previous models	
Battery	NA	kg		0,000						Lead battery Northstar	
Electronics	IC c-t-g from GaBi	cm2		1,550				0%		Linear regression on GaBi data points	
Electronics	PCB c-t-g from GaBi	m2*#layer		30,038				0%	Linear reg y=30,038x+62,63	Linear regression on GaBi data points	
Power supply	NA	kg		0,000							
Mechanicals	Die casting supplier1	kg Al		12,000		Elec (48,4MJ chines	11,2	93%		Internal GaBi models from [1]	Not disclosed in demo version
Mechanicals	Die casting supplier2	kg Al		15,000		Elec (65,1MJ chines	15	100%		Internal GaBi models from [1]	Not disclosed in demo version

Figure 18: **PEEC production sheet.** List of emission factors for production processes (column E), most of them extracted from previous GaBi models (column D) and cleaned from transport figures (column F), as explained in Subsection 4.4.2.



Transport and packaging

Emission factors

	2019 Ericsson sustainability report [2] (used here)		LCA for RBS [1]	
	kgCO2e/tkm	kgCO2e/kgkm	kgCO2e/tkm	kgCO2e/kgkm
Sea	0,012	0,000012	0,017	0,000017
Air	0,65	0,00065	0,8	0,0008
Road	0,073	0,000073	0,09	0,00009
Train	0,029	0,000029		0

Average inbound transpor	1,00	kgCO2e / kg product+pkging
Average packaging	1,51	kgCO2e / kg packaging material

→ comes from GaBi model, GWP ReCiPe result on the average packaging material composition mentionned in [1]

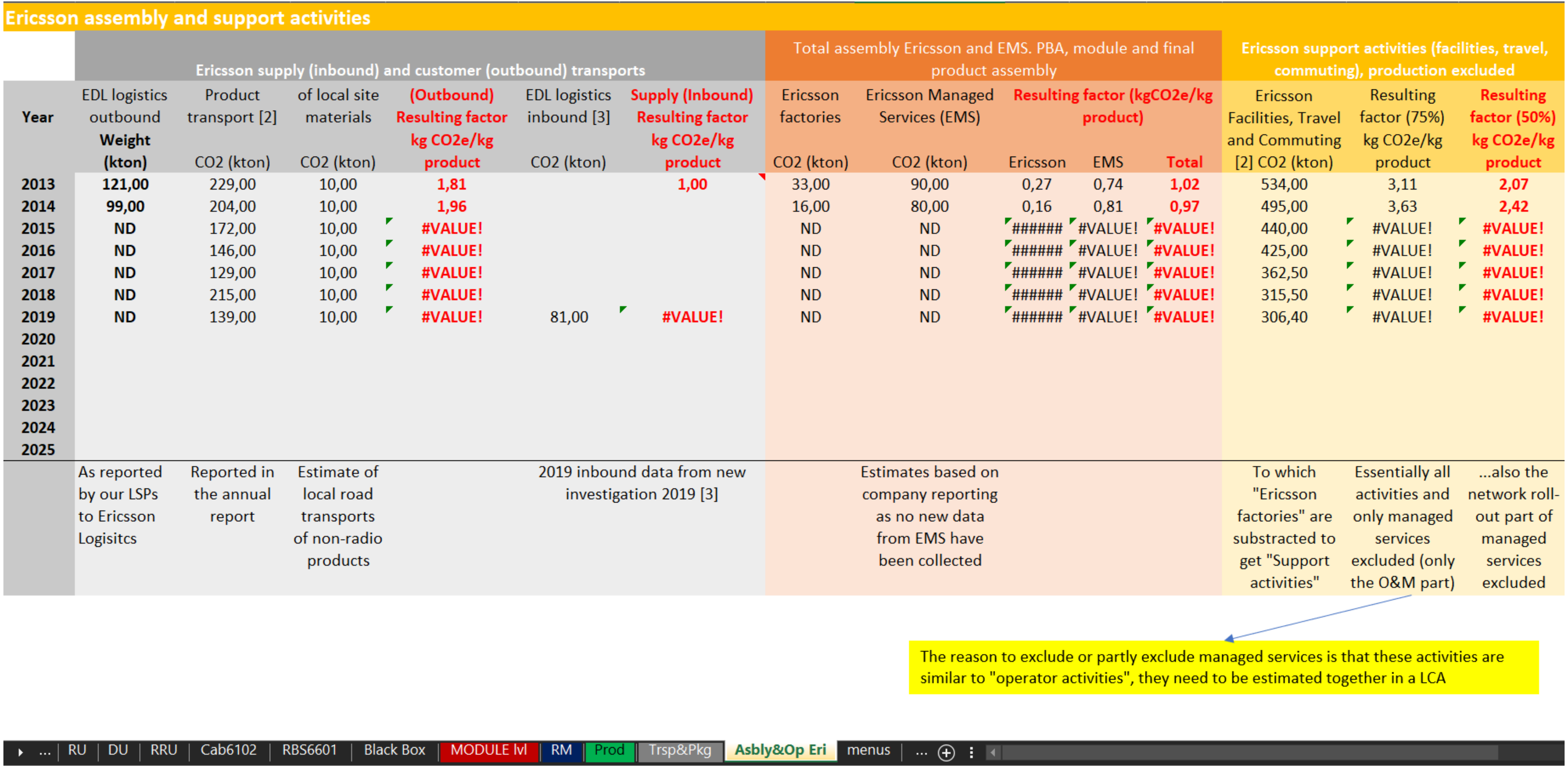
Calculations (also done directly in the main sheet, here is an exemple with data fetched from one of the INPUT sheet)

			PACKAGING		TRANSPORT to assembly						
	Mass (from INPUTS sheet)	**Packaging factors [1]**	**Mass of packaging (kg)**	**Carbon footprint (kgCO2e)**	**Mass of transported good (kg)**	**Sea (km)**	**Air (km)**	**Road (km)**	**Train (km)**	**Impact per kg**	**Carbon footprint (kgCO2e)**
Electronics	2,50	3	5,00	7,55	7,50	0	7913	277		5,16	38,73
Electromech	0,00	1,15	0,00	0,00	0,00	8043	0	1332		0,19	0,00
Mech											
Die casting	13,00	1,15	1,95	2,94	14,95	0	7807	247		5,09	76,14
Other mech	7,00	1,15	1,05	1,59	8,05	13507	0	883		0,23	1,82
Cables	0,00	1,15	0,00	0,00	0,00	1866	267	3199		0,43	0,00
Power supply	0,00	1,15	0,00	0,00	0,00	14750	0	250		0,20	0,00
Battery	0,00	1,15	0,00	0,00	0,00	7951	0	457		0,13	0,00
TOTAL before assembly			8,00	**12,08**							**116,69**
Assembled product	22,50	1,15	3,38	**5,10**	25,88	3500	2500	1000	0		**45,02**

Drop-down menu

fetched from INPUTS sheet

Figure 19: **PEEC transport and packaging sheet**, providing background data for calculation of packaging and transport emissions, as described in Subsection 4.4.3.



Ericsson assembly and support activities

	Ericsson supply (inbound) and customer (outbound) transports						Total assembly Ericsson and EMS. PBA, module and final product assembly					Ericsson support activities (facilities, travel, commuting), production excluded		
Year	EDL logistics outbound **Weight (kton)**	Product transport [2] CO2 (kton)	of local site materials CO2 (kton)	**(Outbound) Resulting factor kg CO2e/kg product**	EDL logistics inbound [3] CO2 (kton)	**Supply (Inbound) Resulting factor kg CO2e/kg product**	Ericsson factories CO2 (kton)	Ericsson Managed Services (EMS) CO2 (kton)	**Resulting factor (kgCO2e/kg product)** Ericsson	EMS	**Total**	Ericsson Facilities, Travel and Commuting [2] CO2 (kton)	Resulting factor (75%) kg CO2e/kg product	**Resulting factor (50%) kg CO2e/kg product**
2013	**121,00**	229,00	10,00	**1,81**		**1,00**	33,00	90,00	0,27	0,74	**1,02**	534,00	3,11	**2,07**
2014	**99,00**	204,00	10,00	**1,96**			16,00	80,00	0,16	0,81	**0,97**	495,00	3,63	**2,42**
2015	**ND**	172,00	10,00	**#VALUE!**			ND	ND	######	#VALUE!	**#VALUE!**	440,00	#VALUE!	**#VALUE!**
2016	**ND**	146,00	10,00	**#VALUE!**			ND	ND	######	#VALUE!	**#VALUE!**	425,00	#VALUE!	**#VALUE!**
2017	**ND**	129,00	10,00	**#VALUE!**			ND	ND	######	#VALUE!	**#VALUE!**	362,50	#VALUE!	**#VALUE!**
2018	**ND**	215,00	10,00	**#VALUE!**			ND	ND	######	#VALUE!	**#VALUE!**	315,50	#VALUE!	**#VALUE!**
2019	**ND**	139,00	10,00	**#VALUE!**	81,00	**#VALUE!**	ND	ND	######	#VALUE!	**#VALUE!**	306,40	#VALUE!	**#VALUE!**
2020														
2021														
2022														
2023														
2024														
2025														
	As reported by our LSPs to Ericsson Logisitcs	Reported in the annual report	Estimate of local road transports of non-radio products		2019 inbound data from new investigation 2019 [3]			Estimates based on company reporting as no new data from EMS have been collected				To which "Ericsson factories" are substracted to get "Support activities"	Essentially all activities and only managed services excluded (only the O&M part)	...also the network roll-out part of managed services excluded

The reason to exclude or partly exclude managed services is that these activities are similar to "operator activities", they need to be estimated together in a LCA

Figure 20: **PEEC assembly and support operation sheet**, providing background data for assembly and support operation emission factors, as described in Subsection 4.4.4.

TRITA-EECS-EX-2021:73