

Deliverable D4.2

Methodology to measure the environmental impact described

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Action number: #101138859

Action Acronym: DILAPRO
Action Name: Digital Laser Production

Deliverable Due date: 31.12.2024
Deliverable hand-in date: 19.12.2024

Revision	Date	Author/Organisation	Description
1	18/11/2024	Magdalena S. Müller/DTI	First Draft
2	03/12/2024	Ana Queiros/EWF	Review by DQCC
3	04/12/2024	Magdalena S. Müller/DTI	Revision of DQCC comments

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Executive Summary

This deliverable, D4.2, outlines the methodologies used to measure the environmental impact within the DILAPRO project. It focuses on data collection methods and discusses briefly the lifecycle inventory analysis and different types of data occurring in a life cycle inventory. The methodologies described provide a framework for measuring the environmental and economic impacts of the laser manufacturing technologies (LPBF, DED, and LST). The deliverable describes the template used for data collection and the preparation process of the template for the respective use cases.

The Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) will only focus on selected use cases (C3, C6, C7, and C10). For these use cases, the system boundaries and functional units are described in this deliverable. Overall, the system boundaries will include the raw material extraction, the laser manufacturing process, the process finalization, and the qualification and certification.

This deliverable describes the different types of data that will be used when performing the LCA. To gather as much high-quality data as possible, customized templates were developed and are described in this deliverable.

Overall, this deliverable gives a general overview of the process of defining the Life Cycle Inventory (LCI) for an LCA study on the example of the selected DILAPRO use cases. It lays the groundwork for performing the data collection and LCA in the next steps of WP4.

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List of Abbreviations

AM	Additive Manufacturing
CRM	Centre de Recherches Métallurgiques
DCU	Dublin City University
DED	Directed Energy Deposition
DILACERT	Digital Laser Certification
DILAFACT	Digital Laser Factory
DTI	Danish Technological Institute
IQ	Installation Qualification
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LPBF	Laser Powder Bed Fusion
LST	Laser Surface Texturing
OQ	Operational Qualification
P.ADD	Prima Additive
PQ	Performance Qualification
R&D	Research and Development
WP	Work Package

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1. Introduction

The DILAPRO project aims to enhance the sustainability and efficiency of laser manufacturing technologies. Measuring the environmental impact of these technologies is crucial for guiding R&D activities and ensuring alignment with sustainability targets. By unveiling hot spots, for example, the LCA work within DILAPRO can guide technical R&D work within the project to focus on these environmental hotspots. This deliverable describes the methodologies for conducting LCA and LCC analyses, which are fundamental for evaluating and optimizing the project's environmental and economic performance.

The methodologies for LCA and LCC are based on international standards, including ISO 14040:2006 and ISO 14044:2006, ensuring robustness and credibility. These methodologies provide a systematic approach to assess the environmental and economic impacts of the technologies used in the project.

The goal and scope of the LCA performed within DILAPRO are already described in D4.1, however, there are some additions and clarifications made in this deliverable, as the inventory and data collection are defined more precisely here. Only selected use cases, as displayed in Table 1, will be analyzed, namely C3, C6, C7, and C10. The use cases were selected to reflect all laser manufacturing technologies within the DILAPRO-project, as many different materials as possible, and most pilot lines will be involved. One use case, C3, representing the LPBF process, will be manufactured at DTI's and Fieldmade's pilot lines to investigate the influence of different machine manufacturers on the environmental impact of the same product. The only pilot line not involved is DCU's LPBF pilot line PL5. In the LCA, specific emphasis will be placed on environmental hot spots during production. These hot spots will be compared to the currently used printing parameters and recent research results. Based on this, recommendations will be made to improve the manufacturing processes and reduce the environmental impact of the identified hotspots.

Table 1 Overview of selected use cases.

Use Case	Name	Process	Material	Owner	Pilot Line
C3	Spring Shoe	LPBF	Inconel 625	Fieldmade	PL4 (Fieldmade) and PL3 (DTI)
C6	Control Valve	LST	316L	DCU	PL6 (DCU)
C7	Centrifugal Impeller	DED-repair	316L	P.ADD	PL2 (P.ADD)
C10	Launch Interface Ring	DED	A20X	CRM	PL1 (CRM)

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The approach to the LCA and LCC is described more in depth in D 4.1 and will be revisited during the reporting of the LCA and LCC in D4.3. This deliverable, however, will focus on the data collection to evaluate the environmental impacts.

A structured approach to collecting relevant data during an LCA contains the following three steps

1. Planning of the collection and outlining of the Life Cycle Inventory (LCI) blocks,
2. Data gathering using the LCI blocks, and
3. LCI blocks finalization (Saavedra-Rubio et al., 2022).

2. Definition of System Boundaries and Functional Units

2.1 System Boundaries

In D4.1, system overviews of all three laser manufacturing technologies were created. Based on those, the system boundaries were defined and can be found in Figure 1, 2, and 3. As shown in the figures, for all systems the boundaries include similar steps: the raw material extraction, the laser manufacturing process and the process finalization steps, as well as the qualification and certification. In the qualification and certification, not only the manufacturing of the additional parts will be considered, but also the testing itself. Planned maintenance will be considered as well, if it is possible to allocate it to a single build job, e.g., if the recoater lib or the filters are changed after every build job. However, excluded are most background processes, such as manufacturing of the equipment, as those are expected to only have a minor impact on manufacturing one of the use cases, the process preparation, including the preparation of a CAD file and simulations, as those are expected to have a minor impact compared to the production, and the post-processing, as DILAPRO is focusing on the laser-manufacturing processes and those processes will not be included in the DILAFACT software either. Additionally, failed builds will be excluded from the LCA, so first-time-right manufacturing is assumed. This might decrease the accuracy of the LCA and would have provided a valuable addition, considering that the DILAFACT software may contribute to fewer failed builds. However, currently no data on the portion of failed builds for the specific use cases exist and collecting these data to a statistically relevant level is not feasible within the scope of WP4.

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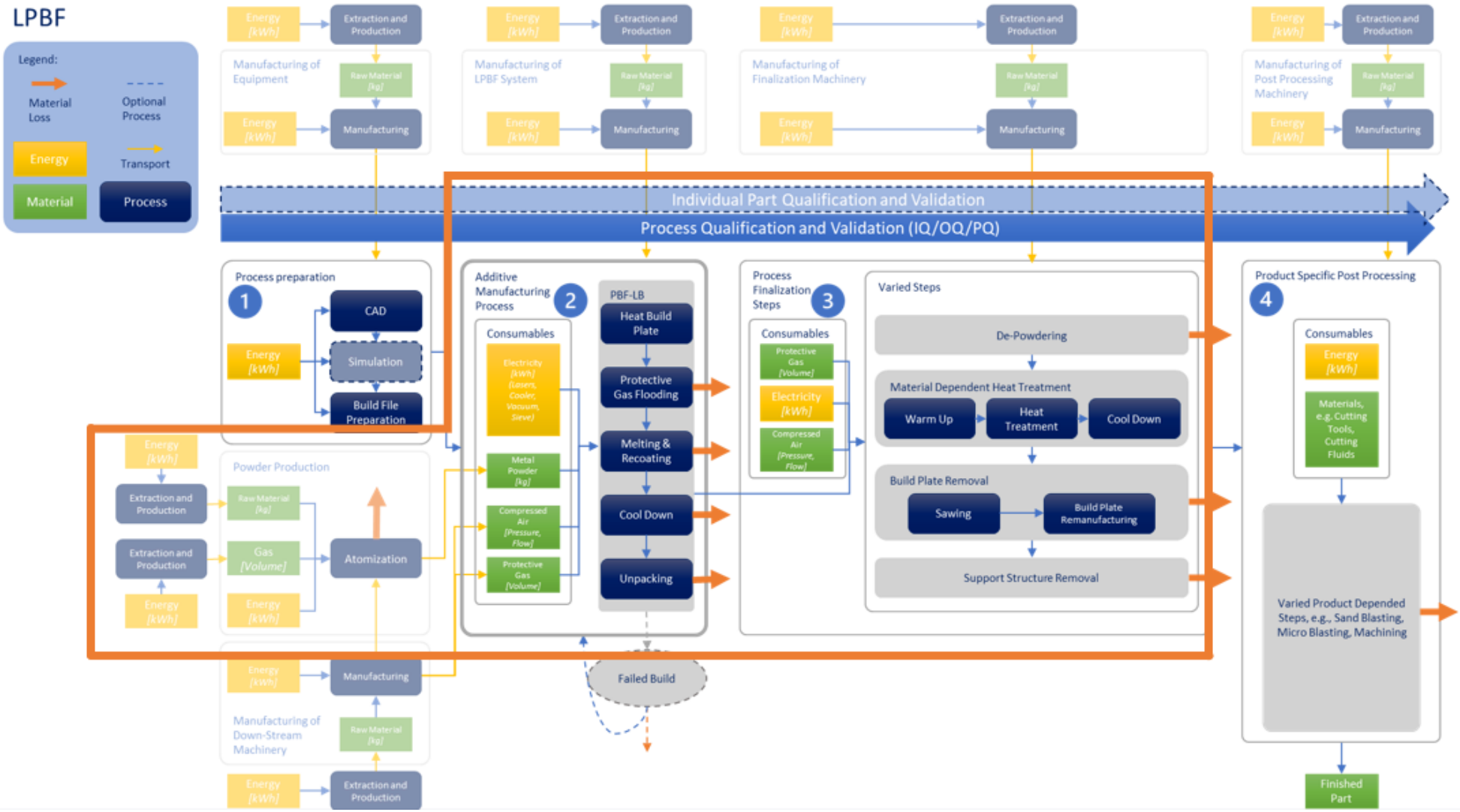


Figure 1 System boundaries in the LPBF process

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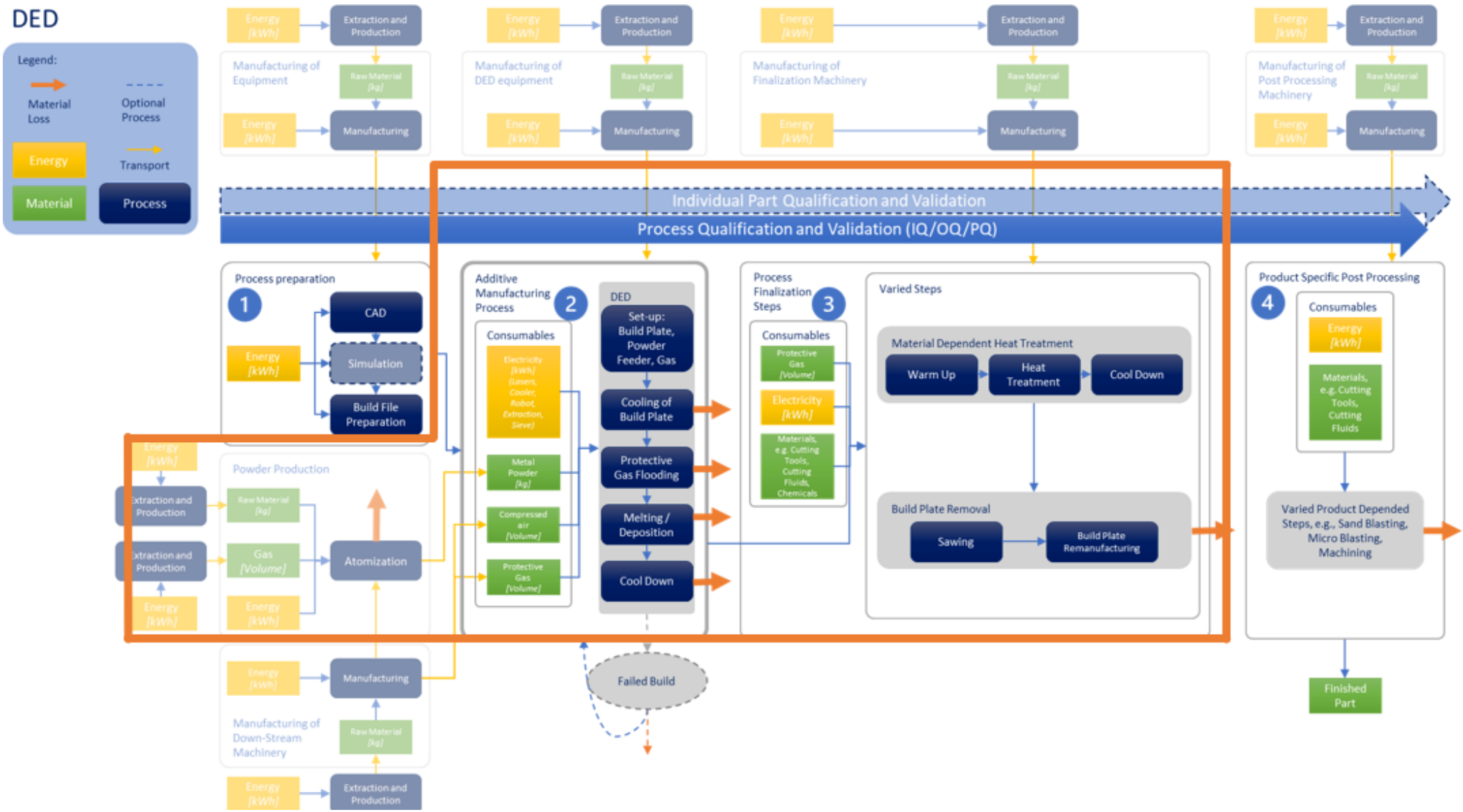


Figure 2 System boundaries in the DED process

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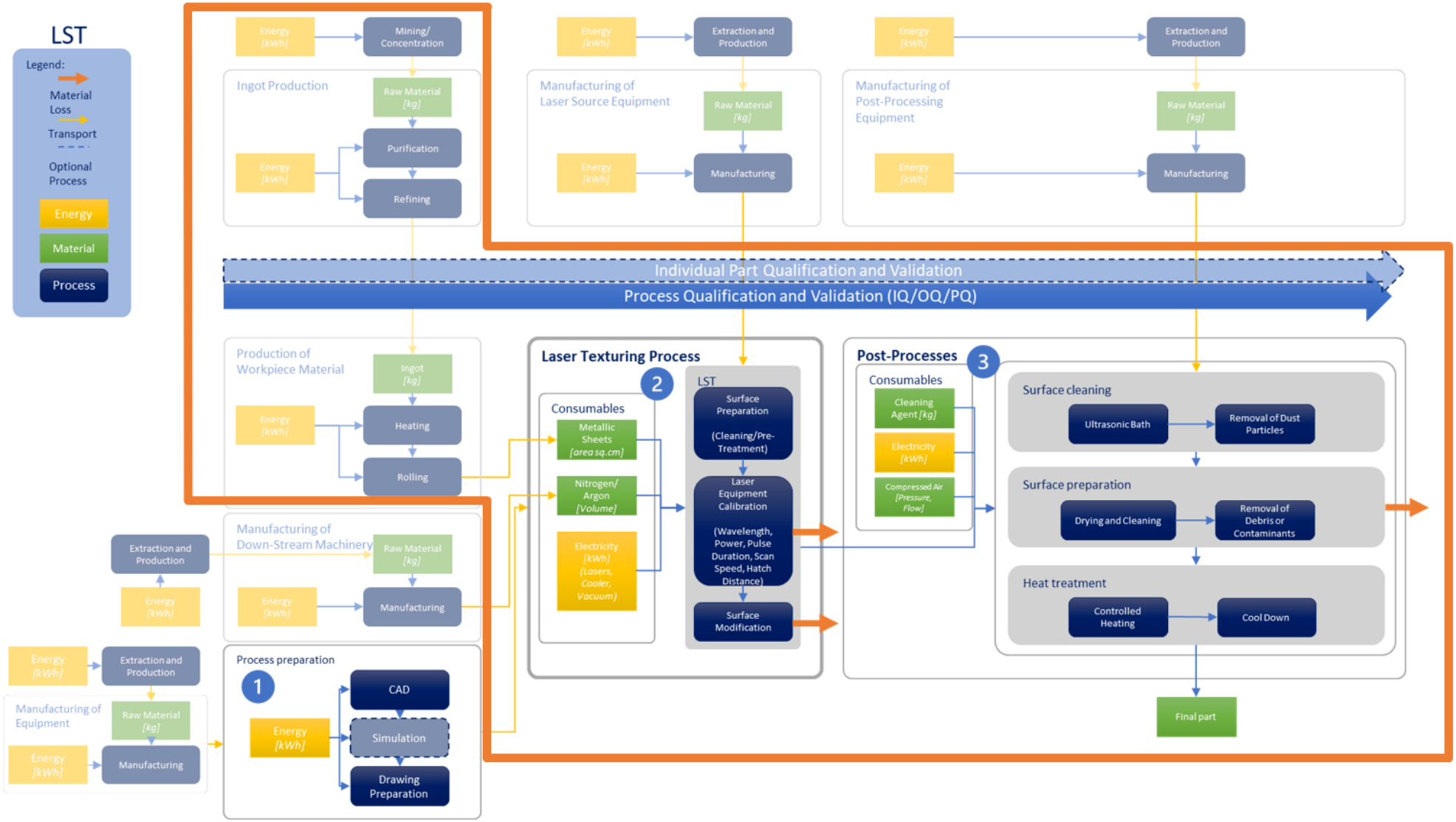


Figure 3 System boundaries in the LST process

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2.2 Functional Units

The functional units are defined based on the use case descriptions given in D1.1. The functional units might be adapted further, e.g. to specify further standards for part qualification, which are currently not specified. Most of the production facilities do not yet fulfill the requirements of ISO/ASTM 52920:2023, which is mentioned in the functional units to describe manufacturing practices. However, this was kept as part of the functional units as it was set as one of the requirements in the use case descriptions in D1.1. It is assumed that this will not impact on the result of the LCA, if implemented afterwards.

2.2.1 Functional Unit and Reference Flow for C3

Functional Unit:

- A “spring shoe” (complex bracket component) that is part of the damping system and fits the mounting points of the equipment and the spring, and transfers loads to springs. The spring shoe must withstand temperature ranges from -30 ^{o}C to 40 ^{o}C and dynamic loading due to harsh driving conditions dampened by springs. The spring shoe fulfils the qualification requirements. The production is according to ISO/ASTM 52920:2023.

Reference Flow:

- Spring shoe and four tensile bars and four density cubes

2.2.2 Functional Unit and Reference Flow for C6

Functional Unit

- A valve to control the fluid flow in pharmaceutical or food industry applications with the ability to withstand corrosion and fouling. The valve is submerged in fluid and must withstand a temperature range from -15^{o}C to 115^{o}C and is made from 316L stainless steel. The valve is produced according to ISO/ASTM 52920:2023 and fulfils the certification requirements.

Reference Flow:

- Two control valves

2.2.3 Functional Unit and Reference Flow for C7

Functional Unit:

- The repair of a centrifugal impeller for the application in an oil & gas installation with worn down blade tips made of 17-4PH. The worn down will be replaced by a DED process with 316L stainless steel. The repaired blades must withstand

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turbulent fluid flow and significant loading (how much?) during operation. The repair must follow ISO/ASTM 52920:2023 and fulfil the certification requirements.

Reference Flow:

- The repaired impeller and the required certification coupons

2.2.4 Functional Unit and Reference Flow for C10

Functional Unit:

- A launch interface ring which is connected to the launcher via a clamp band, which is untightened to set the launcher free, the design must ensure the attachment to the clamp band. The ring remains with the launcher after separation and is a single use item and is mission critical. The launch interface ring must withstand accelerations and vibrations, solar radiation and vacuum. It is made from A20x, and the production must follow ISO/ASTM 52920:2023 and ECSS-Q-ST-70-45C. The launch interface ring needs to fulfil the certification requirements.

Reference Flow:

- A launch interface ring and the certification coupons

3. Data Collection Methods

Accurate and comprehensive data collection is the cornerstone of effective Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) analyses. The quality and type of data can impact the result of an LCA drastically (Finnveden, 2000). Different data sources usually provide data of different quality. On-site data, e.g. data gathered through measuring with sensors applied on the pilot line machines, will provide the highest quality, while on the other hand, generic data will have the lowest quality. The aim within DILAPRO is to collect as much data as possible on site, aiming for the highest possible quality of data and therefore the best result possible. Figure 1 gives an overview and a short description of the data types in an LCA. Data collected on site has the highest quality, while generic average data, for example found in databases such as Ecoinvent, was assessed to have the lowest quality.

As on-site data is of the highest quality, DILAPRO aims to collect as much data as possible directly on the pilot lines. However, there will be gaps in the data, especially for processes not taking place directly at the pilot lines, for example the raw material extraction and the production of the workpiece material. For these processes data from the supplier will be requested and if data directly from the supplier is unavailable, literature data, technical documentation data, calculated data or generic data will be used based on availability. Data will be collected from

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project partners using standardized templates to ensure consistency. Primary data sources include energy consumption, material usage, emissions data, and, for the LCC, operational costs.

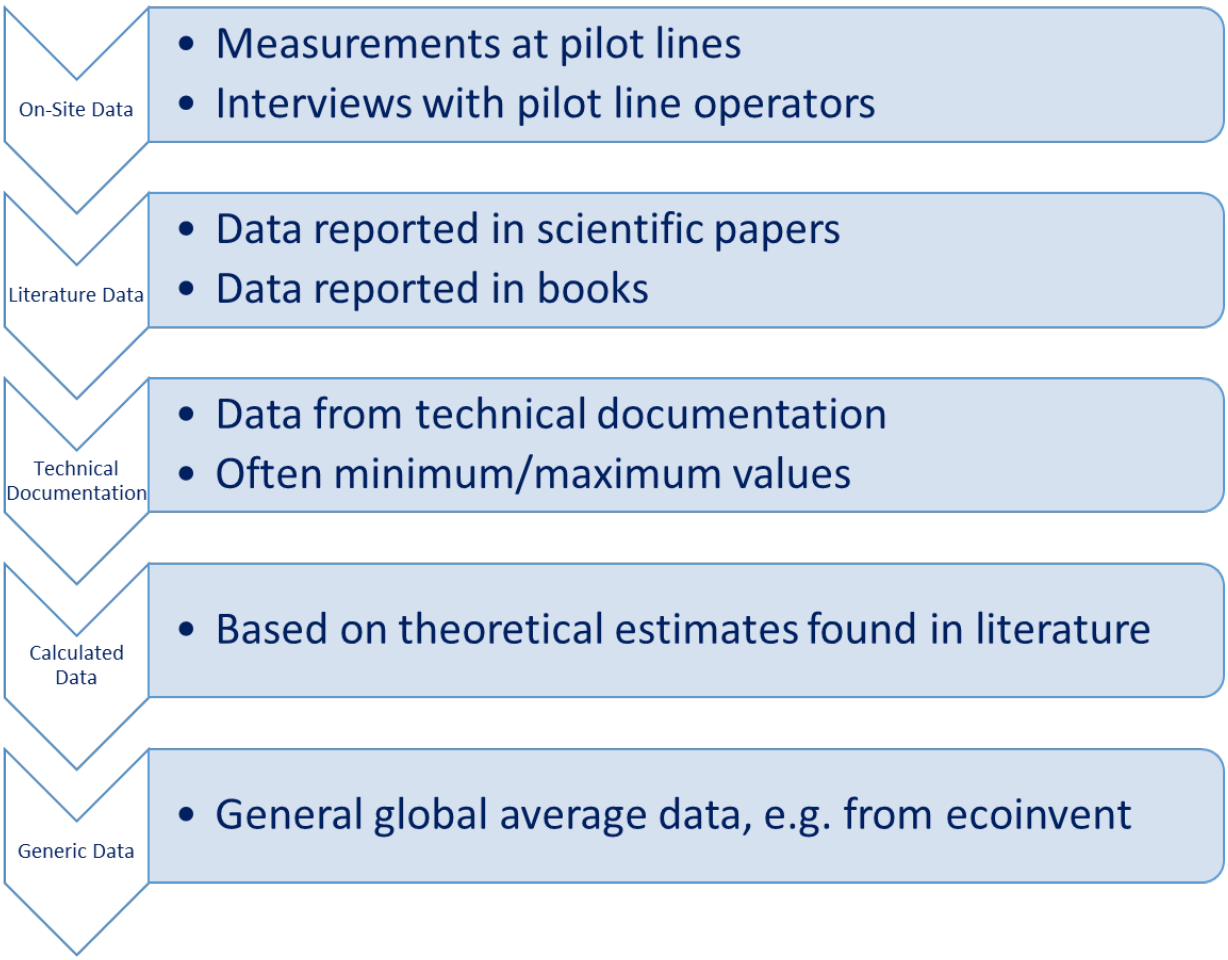


Figure 4 Data quality matrix. On-site data has the highest quality, while generic data from databases has the lowest quality.

Different measurement tools, such as energy meters, machine logs, and material usage logs will be used for data collection. Data that cannot be measured directly might be calculated based on technical documentation, e.g., the gas usage in the LPBF process. The collected data will be logged in standardized data collection templates, developed based on a publication by (Saavedra-Rubio et al., 2022).

The data collection process will consist of the following steps:

1. Development of the templates,
2. Distribution of the templates,
3. Data recording,
4. Submission, and
5. Review and validation.

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Potential challenges include data inconsistencies, incomplete data and data accuracy. Data inconsistency is mitigated by the standardized templates. Incomplete data will be supplemented using secondary data from databases and relevant literature sources as well as follow-up procedures with the pilot line owners. Data accuracy is ensured through regular calibration and validation checks as well as redundant measurements where feasible.

The cost data used in the LCC will be collected primarily directly from the project partners, who will be asked to report on expenditures such as energy costs, consumables, and possibly labor. If necessary, public databases for life cycle cost data, such as London Metal Exchanges, the World Bank, or the European Stock Exchange, will be consulted.

4. Building of the Life Cycle Inventory

As a first step, before the data collection can be performed, the Life Cycle Inventory (LCI) needs to be identified. To build the LCI, the methodology described by Saavedra-Rubio et al. was used and the template provided as supplementary material was used and adapted to the respective DILAPRO use cases. The generic template by Saavedra-Rubio et al. is provided in the Zenodo database (10.5281/zenodo.6577227) and an example of the adjusted templates uploaded to Zenodo (10.5281/zenodo.14328214 at the EU Open Research Repository for DILAPRO, https://zenodo.org/communities/dilapro/) when the LCI and LCA are completed. Saavedra-Rubio et al. identified three steps to guide the data collection:

1. Planning of the data collection,
2. Data gathering process, and
3. LCI block finalization.

The planning step might be the most significant step. It follows the system definition (by system boundaries and functional unit) and consists of the definition of the LCI data requirements, as done in section 3, a preliminary definition of the LCI blocks, and using the defined blocks to customize the generic template.

Based on the system mapping in D4.1, preliminary LCI blocks were defined. To follow the structure of the LCI data collection template, the system mapping was restructured and adapted to the use cases based on the suggestion in (Saavedra-Rubio et al., 2022). An example for use case C3 can be found in Figure 5, and will be described in detail in the following section. To ensure this restructuring and the definition of the LCI blocks is relevant for all use cases, a workshop with the use case owners and all interested project partners was hosted. The use case owners were requested to create a similar overview for their respective use cases and based on this to customize the provided generic template.

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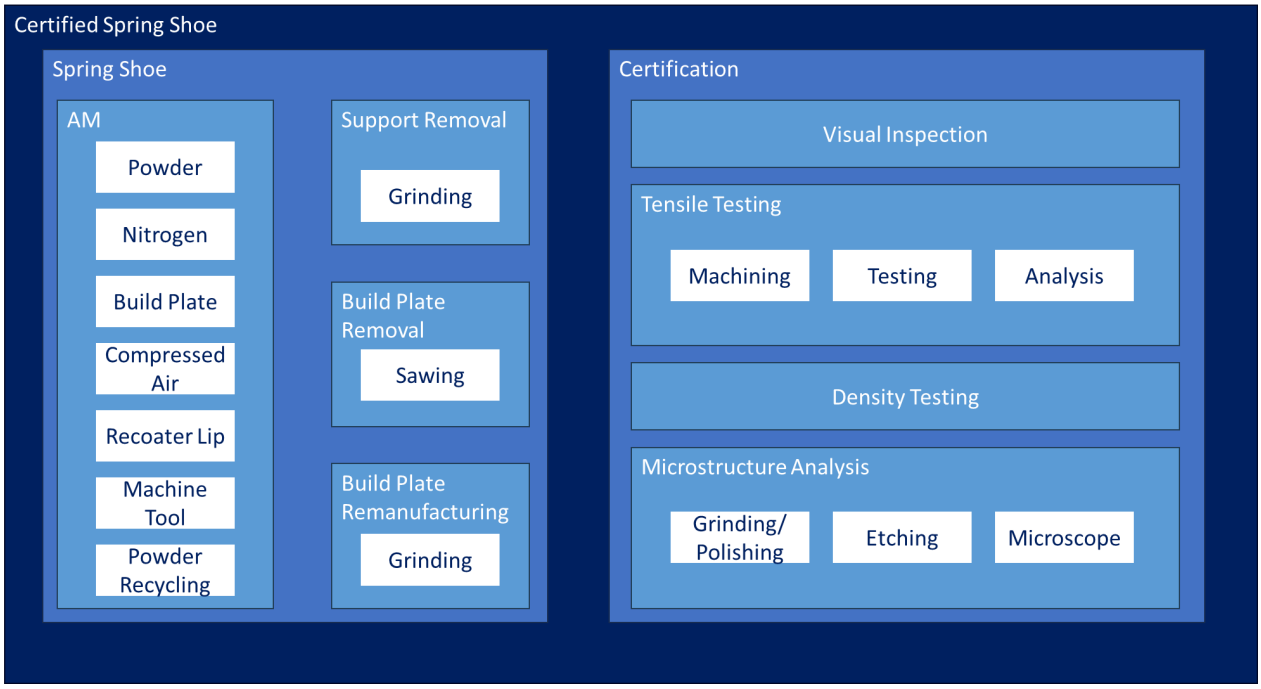


Figure 5 Block diagram of the manufacturing process of use case C3.

The last two steps, i.e. the data collection and the LCI block finalization, will be done in subsequent steps after the finalization of this deliverable and are therefore not described here. The data collection methods, however, are described above already.

4.1 Structure of the Data Collection Template

One main goal with the data collection template is to ensure data consistency and reliability. The template includes specific data fields for energy consumption, material usage, emissions, and costs.

The original template is an Excel file containing eight pages; metadata, read me, contact details, manufacturing, use phase, end of life, references, and feedback. However, due to the cradle-to-gate approach of the LCA in DILAPRO, the pages regarding the use phase and end of life were removed from the template. Next, the page regarding manufacturing was adapted to the processes in the different use cases. An example of one of the tables on the manufacturing page can be found in Figure 6.

Figure 5 shows the preliminary LCI blocks, which also gives a visual representation of the structure of the tables in the template, with the example of use case C3. The template starts with a table at a high level of overview (the dark blue box in Figure 5) and then zooms in through the next tables (medium blue boxes) to arrive at the finest level of detail (light blue boxes with input from white boxes). In the template, each table represents an LCI block which corresponds to a component or subprocess of the main system.

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To further detail with the example of C3, as in Figure 5, the first table in the template will identify the main components of the “certified spring shoe”. These components could be the spring shoe, the certification parts and the certification itself. In the next table of the template, we are going to zoom in on the spring shoe and identify what we need to produce that. The last step is then a zoom-in to what will be needed for e.g. the AM, including powder, nitrogen, build plate, etc.

In this way, we are zooming in more and more towards less processed materials like raw materials. Each zoom-in stage will be represented by a separate table. The tables should reflect how much energy and materials are needed to produce 1 reference flow. In the template, different inputs and outputs for each box (e.g. energy, powder, gas) are specified. The use case owners were requested to split the processes up to a level where they still can measure inputs and outputs, but not below. Further instructions on how to fill in the template can be found on the “read me”-sheet, which is included in the template.

The individualized templates were developed at the workshop. After the workshop, the customized templates were discussed further and completed with the use case owners. In fulfilment of Milestone 7 – Methodology to measure the environmental impact described and defined, the prepared templates were uploaded to the DILAPRO TEAMS/SharePoint, and an email was sent to all pilot line owners and the project manager. Now, the use case owners will record relevant data using the templates provided. It will be considered to submit the completed templates to the central data repository DATAmaestro lake to have easier access when creating the software. The submitted data will be reviewed for completeness and accuracy. If there are any discrepancies or gaps these will be addressed through a follow-up with the respective data provider. Based on this the LCI will be built and the Life Cycle Impact Assessment (LCIA) will be performed.

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PROCESS 1.1		AM production
To main table:	go to T1	
LINK TO TABLE	#	Inputs materials & consumables
	1.1.1	In625 powder
	1.1.2	304 SS build plate
	1.1.3	Gas filter
	1.1.4	Recoater blade
	1.1.5	Cleaning consumables
	1.1.6	PPE
LINK TO TABLE	#	Outputs (products & byproducts)
	1.1.7	As-built spring shoe and test specimens on build plate
LINK TO TABLE	#	Electricity/heat used for main process steps (adjust below names as needed)
	1.1.8	Electricity for LPBF process
	1.1.9	Electricity for powder vacuum
LINK TO TABLE	#	Water use and emissions to air, water, soil
	1.1.10	Water for powder vacuum
	1.1.11	Argon gas

Figure 6 Example of one table in the data collection template with the filled in inputs and outputs. Data will be collected in columns to the right of the example shown.

5. Conclusion

This deliverable provides a description of the methodologies for measuring environmental impacts within the DILAPRO project. It describes the systematic approach of setting up the data collection templates to create the LCIs for the respective use cases. An overview and description of the data collection templates was presented and different sensors to measure the environmental impact were named. Mitigation strategies for insufficient and missing data were described, as well as strategies to get data where direct measurement is not possible. E.g. technical descriptions of machines and generic database data will be used in these cases. However, the data quality was discussed as well and DILAPRO aims to go for directly measured data whenever feasible. The work described in this deliverable lays a solid foundation for the upcoming tasks and deliverables in WP4. The next steps are the data collection and the building of the LCI. Based on the LCI, the LCIA will be performed, and the results will be interpreted.

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6. References

Finnveden, G. (2000). On the limitations of life cycle assessment and environmental systems analysis tools in general. *The International Journal of Life Cycle Assessment*, *5*(4), 229. https://doi.org/10.1007/BF02979365

Saavedra-Rubio, K., Thonemann, N., Crenna, E., Lemoine, B., Caliandro, P., & Laurent, A. (2022). Stepwise guidance for data collection in the life cycle inventory (LCI) phase: Building technology-related LCI blocks. *Journal of Cleaner Production*, *366*, 132903. https://doi.org/10.1016/J.JCLEPRO.2022.132903

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