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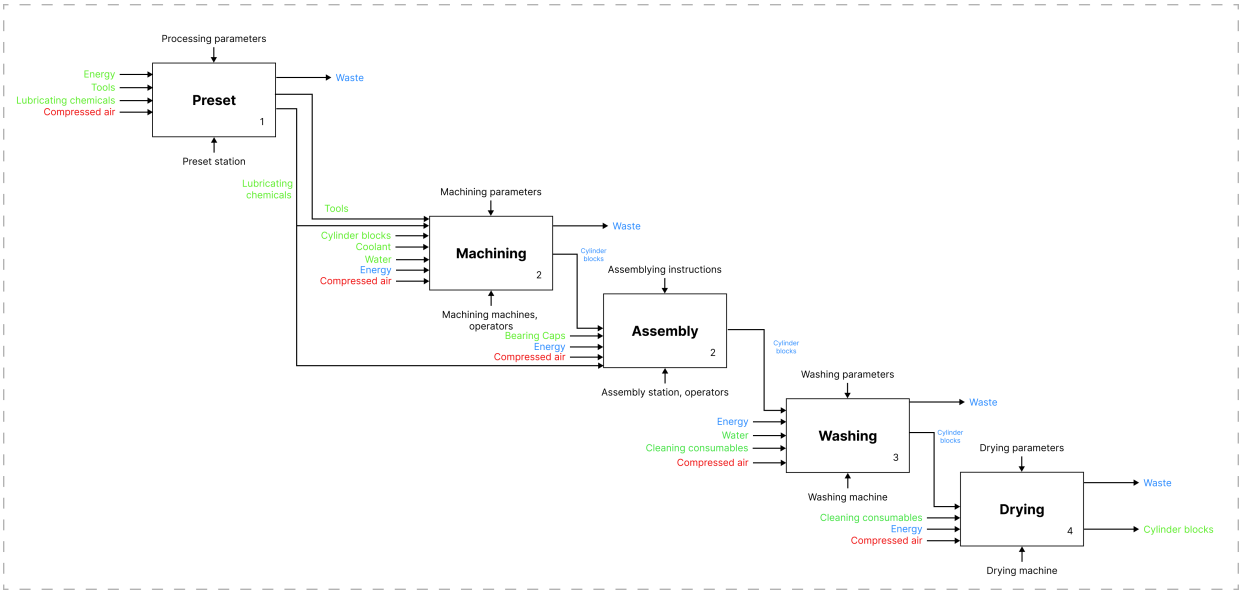

Data-Driven Solutions for Green Production

Integrating Resource Efficiency Assessment in Manufacturing Systems

Master's thesis in Product Development

JUAN GONZALEZ AND THOMMY NGUYEN

DEPARTMENT OF INDUSTRIAL AND MATERIAL SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
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Supervisor: Qi Fang, Deparment of Industrial and Material Science
Supervisor: Lena Moestam, Volvo GTO
Examiner: Mélanie Despeisse, Department of Indutrial and Material Science

Master's Thesis 2024
Department of Industrial and Material Science
Division of Production Systems
VIVACE Research Project
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Process mapping of the manufacturing system of the study case, including data of resources that is available.

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Abstract

In response to sustainable development efforts by the United Nations 2020 Agenda, industries are aiming towards more sustainable production. The European Commission has created the classification system called EU taxonomy, establishing the definition of sustainability and sustainable activities. Consequently, European manufacturers are seeking opportunities to reduce their environmental impact, creating the need to understand how their resources are utilized. Resource efficiency methods enable the assessment of resource usage but require high data quality and availability, making the implementation difficult. One of the main challenges for resource efficiency assessment is data completeness and reliability, especially at a process level, in tandem with a lack of standardized data collection methods resulting in the implementation of RE assessment being difficult. Despite the issues, there are still opportunities and benefits of using already available data in manufacturing systems with proper indicator selection having data characteristics in mind. This project aims to leverage available factory data, select indicators based on available data, and integrate resource efficiency in manufacturing systems to identify opportunities for greener production with a resource efficiency method in line with the EU taxonomy. This project showcases a case study implementing resource efficiency assessment in an automotive plant with an assessment design that includes multiple methods to be aligned with stakeholder priorities and indicates inefficiencies of resource usage. A selection method was devised as the project's core, designed to be general and adaptable for other cases. However, assessment methods are inherently different and data quality is a critical factor in implementing them, not only stakeholder preferences of the company. The study utilized existing data to assess resource efficiency and proposed automated data handling for future assessments to streamline the process and reduce the execution time.

Acknowledgements

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Firstly, we would like to thank our two supervisors for their guidance and support in the project. The insight regarding the academic and industrial perspectives has helped us continuously throughout the study. The industrial contacts given to us through our supervisor have also been invaluable.
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We would like to thank our families for the emotional support, which has been of great importance and served as a pillar of strength in all parts of the project. The encouragement provided has been a great source of motivation and morale in times of need.
Lastly, we would like to thank each other for the mutual support, dedication, and ambition to complete the project and produce meaningful results. We have both navigated personal and project-related challenges and the mutual support given from each other has been essential to making progress in the thesis.
Thank you all for your invaluable contributions and support.

Juan Pablo, González Sánchez & Thommy, Nguyen Gothenburg, May 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AHP	Analytical Hierarchy Process
API	Application Programming Interface
APQ	Availability Performance Quality
EMS-CD	Environmental Management System - Cost Deployment
EVSM	Energy Value Stream Mapping
G-VSM	Green Value Stream Mapping
KPI	Key Performance Indicator
MFA	Material Flow Analysis
MLR	Multiple Linear Regression
NVA	Non-value-added
RE	Resource Efficiency
REC	Resource Efficiency Cockpit
REF	Resource Efficiency Flowchart
RFM	Resource Flow Mapping
RVM	Resource Value Mapping
Sus-VSM	Sustainable Value Stream Mapping
VA	Value-added
VSM	Value Stream Mapping

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables that have been used throughout this thesis.

Indices

i,j,k	Indices for rows, columns, and number of sub-criteria in calculations of weights

Sets

C	Set of identified criteria for RE method evaluation and selection

Variables

C_i	The criteria in position i
$C_{i,k}$	The sub-criteria k, of parent criteria i
$a_{i,j}$	The relative importance of between criteria of row i and column j in pairwise comparison matrix
GM_i	The geometrical mean or score of criteria i
w_i^{parent}	The weight of importance for parent criteria i
$w_{i,k}^{local}$	The local weight of importance for sub-criteria k of parent criteria i
$w_{i,k}^{global}$	The global weight of importance for sub-criteria k of parent criteria i

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1

Introduction

1.1 Background

Due to the current the creation of regulations for manufacturing companies to transition towards sustainable manufacturing, different European manufacturers are looking for opportunities to reduce their impact on the environment, and to achieve that goal, they need to understand how they are using their resources. In this context, resource efficiency (RE) methods offer a structured path to assess resource usage for this purpose. However, to utilize some of these methods, high-quality data with high availability is a requirement, making it challenging to use these methods for factories that do not have this type of data.

As shown in a recent study regarding the exploration of factory data for resource efficiency assessment (Fang et al., 2023), one of the main challenges for performing RE assessment was data completeness and reliability, especially at a process level. Although most of the data needed for performing basic RE was collected, at the process level, just a small percentage of the required data was stored. This, among other issues like lack of standardized data collection methods, makes it difficult to perform an RE assessment. Despite this, there are still opportunities for improvement by using already available data in manufacturing systems by selecting proper indicators.

To know how the processes of a manufacturing system are performing in terms of their resources, proper KPIs must be selected so that they can be calculated with the data already collected, or with easy-to-collect data that is missing. In terms of environmental impact, activities can be measured through different indicators, depending on the indicator set. Examples of such are material consumption, energy consumption, water consumption, and land use, among others (Joung et al., 2023). Since these indicators require different data across the processes, to be able to find opportunities, it is necessary to make a proper decision regarding the selection of these, taking into consideration available data, the company's objective, and the value added to the assessment.

Due to the challenging nature of this situation, research projects supporting manufacturing companies are currently being held to help them make the transition. This is the case of the VIVACE project (Chalmers Tekniska Högskola, 2023), which con-

sists of creating a toolbox to manage environmental performance according to EU sustainability requirements. The aim is to contribute to three specific sustainable development goals (United Nations, 2015): sustainable consumption and production patterns (SDG12), action to combat climate change and its impact (SDG13), and promote sustainable industrialization and foster innovation (SDG9). In this sense, and specifically, to contribute to SDG12, it is highly relevant to explore the possibilities of RE assessments that can be performed with already available data so improvement opportunities can be found in different production systems.

1.2 Research objectives

This project aims to leverage factory data to integrate resource efficiency assessment in manufacturing systems. To achieve the aim, power train manufacturing facilities are selected to identify opportunities for greener production by applying a suitable RE method that is in line with the EU taxonomy. Based on this, these are the three objectives of the project:

- Identify RE methods capable of quantifying indicators specified in the EU taxonomy as well as other standardized indicators such as life cycle impact categories and environmental footprint, aligning with the expectation of the case company.
- Identify the type of data already available in existing manufacturing systems that can be used to perform RE assessments.
- Conduct the RE assessment (which may require filling data gaps, if any) and propose solutions to automate data handling for future assessments.

1.3 Research questions

Based on the aim and goals described earlier, the following research questions are formulated:

- How can a manufacturing company select a suitable RE assessment method?
- How can a RE assessment be performed with the available data already collected by the company?
- How can a manufacturing company benefit from RE assessment activities?

1.4 Limitations

There are four major limitations in this project regarding the scope:

- First, one of the main important ones is data availability. In the project, the data that will be used for the project is the one that is already available at the company, to avoid any expenditures on buying technology for data collection.

- Second, since the concept of resource in an RE assessment is quite broad, this concept will cover everything that adds value to the production system and generates a significant environmental impact according to the KPIs selected.
- Third, although there are different indicators set, the ones that will be used will be aligned with the EU sustainability requirements, which includes the most recent version of EU taxonomy.
- Fourth, the assessment will not be performed in the whole life cycle of the main product, but rather in specific areas of the production that are relevant according to the research, the goal of the company, and its personnel.

2

Theory

2.1 Resource Efficiency Concept

RE refers to how well a production system utilizes resources to achieve a desired output. It can be defined as eco-efficiency due to its environmental and economic perspective, and it is about improving transformation processes. By increasing eco-efficiency, three targets can be achieved in a production system: reducing consumption of resources, reducing the impact of nature, and increasing the value of used resources (Lundholm et al., 2012a). In this context, the concept of resources is defined as everything consumption required by manufacturing systems to produce goods, including all physical and human resources such as material, energy, machines, and staff.

The evaluation of resource efficiency in production systems cand performed with different methods. According to (Papetti et al., 2019), supporting methods of energy and resource-related analyses can be divided into four groups: modeling and analysis, emissions calculation and sustainability assessment, energy or resource assessment, and benchmarking. The selection of methods will depend on the needs of a company, along with the knowledge, tools, and infrastructure for data collection.

2.2 Resource Efficiency in Manufacturing Systems

Although the idea of using resources efficiently has been explored widely throughout different industries for many years, even resulting in the creation of international standards (ISO) to support companies pursuing this goal (Schmidt & Nakajima, 2013), the main focus has been monetary. However, due to the rise of environmental concern, and the pressure from policymakers towards manufacturing sectors with a high ecological and social footprint, such as the automotive sector (Jasiński et al., 2021), it is not enough for companies to care about reducing costs. Now, they must demonstrate they are making a substantial contribution towards sustainable production with quantifiable data. Therefore, they need to evaluate their processes and measure their environmental impact through multiple assessments, reporting to stakeholders specifically on how their use of resources affects the environment.

This is particularly relevant for the manufacturing sector in which productivity has

grown remarkably over the last decades (Duflou et al., 2012). This reflects how crucial resource efficiency is in the global economy and efficient resource utilization in general. Despite high productivity, the industry is responsible for the highest consumption of some resources. To exemplify this, 51% of the global energy consumption can be attributed to industrial consumption. In this context where companies desire to become more environmentally friendly, they search for methods that can tell how to reduce consumption while simultaneously maintaining their economic advantage.

3

Case study methodology

The study aimed to integrate a resource efficiency assessment in the manufacturing system of the selected company, answering the research questions listed in the process. Based on the literature, the benefits of the case study methodology were aligned with the specific situation. First, according to Meyer, 2001, a case study methodology handles how and why questions well, which is how all research questions were formulated in the study. Second, a single case study methodology is well suited to studying specific phenomena from a certain entity and enables an in-depth understanding of said phenomena (Heale & Twycross, 2018). For the current study, the phenomenon referred to identifying opportunities for greener production with the application of RE assessment in the manufacturing system, and the entity being the manufacturing system of the case company. Third, the case study methodology is known as a triangulated research strategy, where said triangulation can occur with data, theories, or methodologies that reduce biases or errors and increase the reliability of results (Tellis, 1997). Fourth, there is no fixed or defined methodology for a case study, meaning that the case study methodology design for this study could be adapted to the specific case in mind (Meyer, 2001). Due to the listed points, a case study methodology was deemed suitable for the project and a single case study methodology was designed and implemented.

3.1 Case study design

The case study design of the current project was mainly based on (Despeisse et al., 2023) with added and modified activities. A flow chart of main activities in the methodology, expected results and dependencies can be found in Figure 3.1. Activities included a literature review, analysis of the manufacturing system (including observation, qualitative and quantitative analysis), RE method selection, and RE assessment. The arrows in the flowchart show the dependencies of activities and chronological order. Literature review and observation were the main data collection methods which aimed to combine theoretical and academic knowledge with industrial expertise from experts at the case company. Literature review was a continuous activity, that aimed to contribute essential theoretical understanding to perform each activity. As a result, theoretical and industrial understanding was combined at a knowledge and execution level in activities to achieve triangulation,

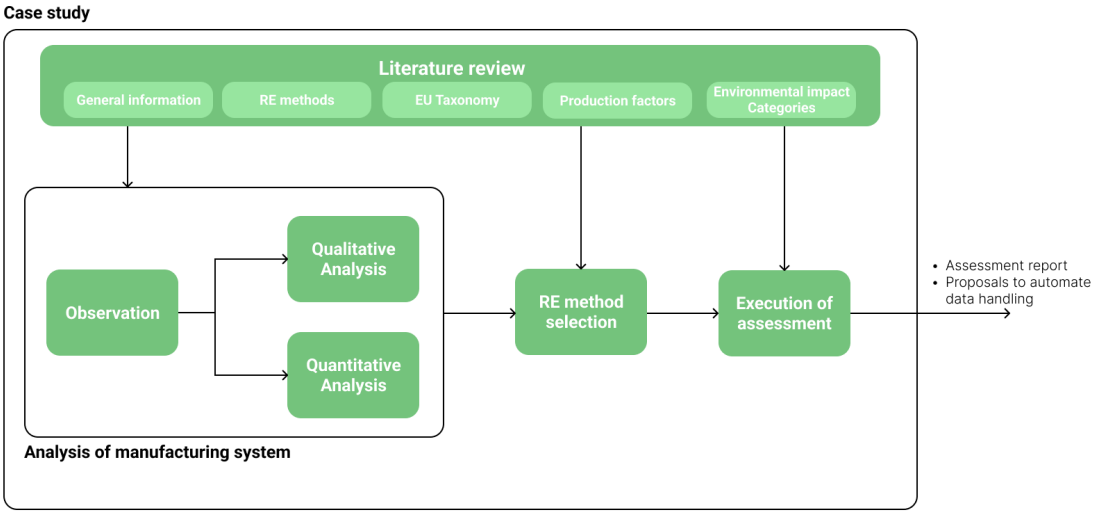

Figure 3.1: Flow chart illustrating main steps

increasing the reliability from the combination of different perspectives. Figure 3.1 mainly illustrates the general sequencing of activities and workflow and the following chapters will explain the steps of the main activities in more detail.

3.2 Literature review

Literature reviews are a fundamental part of research. They give a clear picture of existing knowledge and allow researchers to support their path. To synthesize this existing knowledge, it is possible to conduct a comprehensive scoping review, which is a structured approach used to "determine the coverage of a body of a field of study, indicating, among other things, the volume of literature available in the field, its focus, how research is conducted, and the main gaps" (Chiarello et al., 2021). In this context, the scoping review was performed in a five-stage framework (Arksey & O'Malley, 2005), which divides into identifying the research question of the review, identifying relevant studies, study selection, charting data, and summarizing and reporting. This comprehensive study resulted in a deep understanding of RE methods, selection, and possible adaption of a suitable one for the project. Besides this, a small literature review was performed to understand machining processes later on in the project.

Based on the research questions defined, relevant studies were identified using as main search engines the online library of Chalmers University of Technology (Högskola, 2024) and the web search engine of Google (Google, 2024). Through these engines, a personal database of articles was created, retrieving the articles that were related to the following keywords:

- ("Resource efficiency" OR "Energy efficiency" OR "Efficiency assessment" OR "Efficiency analysis") AND ("Green manufacturing" OR Sustainable produc-

tion")

- "Resource efficiency" AND "Assessment" AND "Method" AND ("Manufacturing" OR "Production")
- "Environmental performance" AND "Assessment"
- "Sustainable" AND "Automotive sector"
- "Consumption factors" AND "Automotive manufacturing"

Before making a thorough reading, they were inspected, checking if they were related to theme RE assessment in manufacturing. Then, once they were examined, they were classified according to the main topic of the article. Topics for classification were method, indicators, method selection, framework, analysis, and state-of-the-art. Since the focus was on the methods, a table was created showing all the different methods found. The following table was used for classification:

Table 3.1: Table used for classification of method

Method	Coverage			Driving factor	Quantifies
	Resource 1	Resource 2	...	(Environmental or	environmental
Method 1				financial or both)	Impact (Yes or No)

As seen, three important aspects were added to the table to classify the methods. The first one is coverage, which refers to which resources the method covers (e.g. Water). The second one is the driving factor, which can be chosen as environmental, financial, or both. Finally, the last aspect was the quantification of environmental impact. While inspecting the articles, it was noticed that, although the majority of articles mention how their method has benefits on the environment, the environmental impact was quantified in just a few of them. This was a relevant aspect because it was desired to cover this aspect in the assessment that was planned to be done for the study case. That means that, if the method selected did not cover this aspect, it was going to be calculated based on a method that did have the calculation.

3.3 Observations

The manufacturing plant for the study case was overseas, meaning that in-person visits were not possible. However, to counteract the possible loss of information due to this situation, data collection, and communication with plant personnel were constantly maintained, so that all the information from the factory would be gathered through virtual presentations of the factory with industry experts, and a review of all necessary documentation that they provided. Based on that, a pilot area to conduct the assessment was selected.

Additionally, a Gemba walk, which was an in-person visit to a production floor to understand its processes (Fang et al., 2023), was performed in a manufacturing plant with similar processes in closer proximity. Although it was a larger manufacturing

plant, they had similar processes, which facilitated understanding of the relevant aspects of production (working set-up, resource utilization, and waste management at each working station). Regular communication was also maintained with the personnel from this plant working under the same concern as the case company.

3.4 Quantitative Analysis

The data collected was explored with the use of graphical visualization. Different methods of visualizing the process data will be used to facilitate data understanding. Examples of visualization methods are static graphs such as scatter plots, box plots, histograms, etc. Visualization is necessary to identify correlations/contrasts in the behavior, structure, and frequency of data from different sources and assess the causes. It also aided in determining the quality of data, enabling the identification of potential data gaps, trends, and patterns in data behavior. Finally, graphical visualization facilitates understanding of data of external parties and will execution of action plans proposed by the study.

3.5 Qualitative Analysis

The following chapter presents the methodology and included activities in the qualitative analysis. The methods described are process mapping, data inventory, resource flow mapping, and the data quality assessment framework.

3.5.1 Process mapping

Following the selection of the pilot area, an understanding of its activities, functional hierarchy, input and outputs to perform activities, and dependencies was necessary. Therefore, process mapping was necessary to map the activities. As a means to achieve this, IDEF0 was utilized to model the pilot area. It is a widely used method for structured analysis and system design for representing a system's functional framework. Activities and processes were presented as boxes with inputs and outputs as horizontal arrows flowing into or out of said boxes, shown in Figure 3.2. Constraints of the activity and mechanisms for the process were represented by the vertical arrows (Liles & Presley, 2023). Different levels of detail were examined with IDEF0, including the production area and its internal function. This aided the analysis and created insights into the pilot area at different levels. The pilot area could then be examined at both a high level or decomposed as sub-processes. Also, flows between the sub-processes and hierarchy were visually represented, highlighting the relations of the sub-processes. The method was also implemented together with data classification of input and output data. Each input and output arrow will be assigned a color depending on the data category, this is further explained in Chapter 3.5.2.

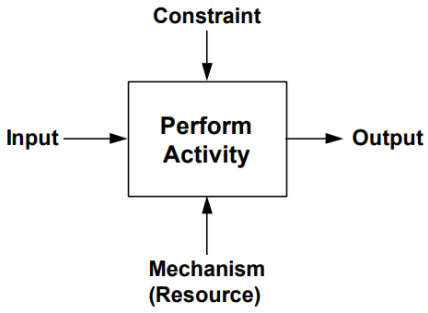

Figure 3.2: IDEF0 Representation (Liles & Presley, 2023)

3.5.2 Data Inventory

This step included gathering process and production data for the pilot area and examining data availability. Data on resource consumption was requested and directly provided by the contact person of the case company in spreadsheet format. Data regarding production factors were directly extracted from the case company's manufacturing monitoring system. An initial screening was conducted. Aspects considered in the initial screening were data not specifically dedicated to the pilot area, unusable due to being highly incomplete, or redundant compared to other files with similar data.

To get an overview of the availability of current process data, the study utilized the classification of input and output data described by Fang et al., 2023. Data were classified into three categories (A-C), defined by data availability and the possibility of allocation of data to the corresponding activity or process. The data classification was implemented with IDEF0 which provided a visual overview of data availability assigned to a specific manufacturing activity or function. In turn, this aided in understanding the data inventory connected to each manufacturing activity at multiple levels and improved visual representation by being centralized in a single mapping. In Table 3.2, the categories and definitions can be found (Fang et al., 2023). Each category is color-coded to ease visual presentation and clarity.

Table 3.2: Data classification and definition (Fang et al., 2023)

Category A	Collected/available and can be allocated	Data in this category are already collected and can be allocated to the corresponding activity/process
Category B	Available/collected but cannot be allocated	Data are available/collected but require extra effort to/cannot be allocated to activities/processes
Category C	Not available	Data are not available in the current production system; Category C requires further investigation or proper estimation in assessments

3.5.3 Resource flow mapping

Although the process mapping provided insights and an overview of the hierarchical relations of processes, it does not clarify details regarding resource flow between

individual processes such as electricity, materials, or process chemicals. A resource flow mapping was implemented combined with spaghetti diagrams representing the flow of resources. A Spaghetti diagram is used for visualizing the continuous flow of activities through processes with a tracing line, enabling the identification of potential waste points and improvement areas (Raikar et al., 2015). This highlights the resources that each machine consumes in production. Also, the area layout is visually represented in the diagram. The specific method was chosen to give a better overview and understanding of the manufacturing system and resource consumption within and across the defined system boundary.

Each process was placed in its corresponding location based on the layout of the pilot area. Then a Spaghetti diagram of flows showing the flow of each resource was constructed. The flows of resources were from one process to another or across the system boundary to/from processes. Traditionally, all flows are presented simultaneously in a single graph. Due to the high quantity of processes in the selected pilot area, the resource flow mapping was divided into multiple layers. Subsequently, each layer represented one resource. This was to improve visual clarity and overall understanding.

3.5.4 Data Quality Assessment framework

The results and reliability of an assessment are affected by the quality of data utilized. Therefore, an evaluation of data quality was necessary to understand the characteristics and its suitability as input for RE assessment and potential implications for produced results. To do this, a two-level framework described by Cai and Zhu, 2015 was utilized for the data quality assessment. The first level consists of five data quality dimensions. It includes data availability, usability, reliability, relevance, and presentation quality, and each dimension consists of one or more elements. The framework was chosen for its broad coverage of characteristics and decomposition from general dimensions into those specific elements. The elements provide further definitions of the dimensions, and based on this, it is possible to tell if the data fulfills or not the dimension. By using this framework, the main purpose was to report data quality to see not only its characteristics but also if those are adequate to perform a RE assessment.

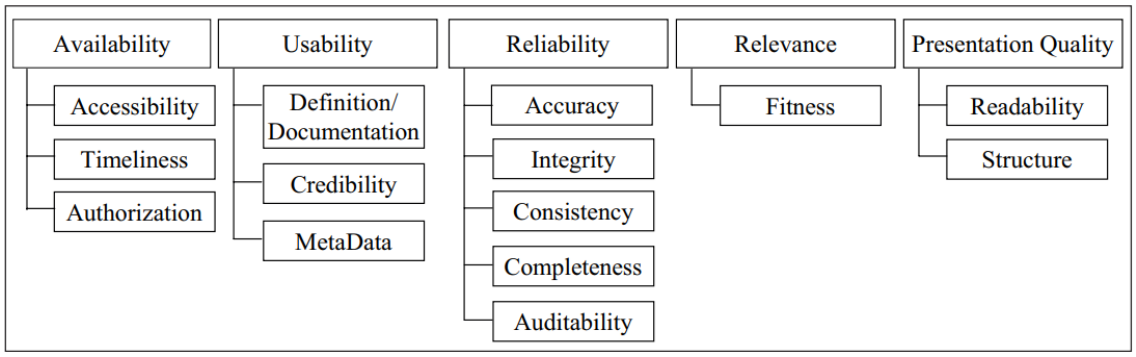

Figure 3.3: Hierarchical data quality assessment framework (Cai & Zhu, 2015)

3.6 Resource efficiency method selection

From a list of potential RE methods, one suitable method that is beneficial for the case company and its needs from a RE assessment was needed. The benefits of executing an RE assessment vary depending on the method. Trade-offs regarding the benefits and the perceived importance from experts and employees in the company were difficult and complex to evaluate qualitatively. Therefore, a systematic methodology was needed to translate qualitative aspects and enable quantitative evaluation of methods concerning the relative importance of criteria reflecting benefits from RE methods and the ranking of their relative importance based on case company priorities. To this end, an AHP approach (Er et al., 2024) was implemented to hierarchically and systematically decompose criteria, assess and select RE methods based on the company priorities of criteria, and design the assessment accordingly. The selection process was divided into three steps:

- Identification of suitable selection criteria.
- Weighting of the relative importance of criteria based on case company priorities.
- Scoring of RE assessment methods for each criterion and final score calculation.

3.6.1 Identification of selection criteria

Selection criteria were identified based on meetings with experts of the case company, the literature review of RE methods, and brainstorming based on information acquired by the first two. The benefits of implementing an RE assessment differ depending on the RE method. Based on the knowledge gained from the literature review of RE methods and expert talk, a brainstorming session was carried out to identify said benefits and requirements to use them. This process was designed such that multiple perspectives could be integrated. Not only is the general understanding of RE methods essential, but it also needs to be contextualized for the manufacturing system to be assessed. The criteria mainly reflected the possible benefits of RE methods and the required assets to utilize them for the selected pilot

area and its system boundary.

3.6.2 Weighting of the relative importance of criteria based on case company's priorities

To collect the company's input regarding the selection criteria, a questionnaire was developed and sent to the employees and experts. The list of all questions and corresponding answers can be found in Appendix A split into two parts. Appendix A.1 shows questions comparing criteria and Appendix A.2 are questions for comparing sub-criteria. The questionnaire consisted of multiple choice questions in which the respondent compared two criteria or sub-criteria. Figure 3.4 illustrates the structure of all questions. A description of the criteria was also included in each question. This was to minimize confusion regarding the definition of each criterion, ensure that the criterion would not be misinterpreted, and minimize backtracking needed from the respondents. The questions were intentionally kept short with few options due to the repetitive structure and to reduce cognitive overload. The number of questions matches the number of unique combinations of comparisons, meaning that redundancy is reduced by not comparing two individual criteria more than once.

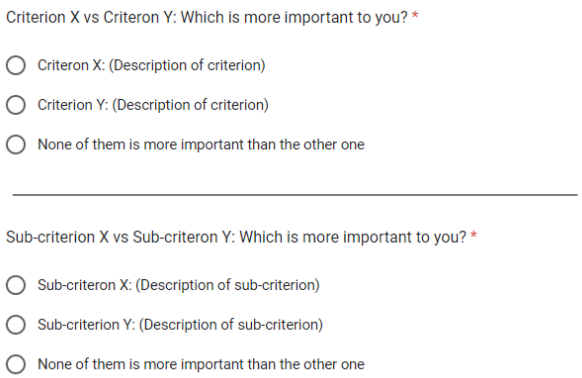

Figure 3.4: Question structure in questionnaire

Based on survey answers, the relative importance of criteria was defined with a pairwise comparison of all criteria and sub-criteria within the same parent criteria. The general structure is exemplified in Table 3.3 where the rows are denoted as i and columns as j. Each criterion C_i is compared against another criterion C_j. The relative importance of C_i compared to C_j is denoted as $a_{i,j}$ in the matrix cells. If a criterion C_i is considered more important than another criterion C_j, the value of $a_{i,j}$ is 3. If they are considered equal, $a_{i,j}$ is assigned the value of 1. Then, for each defined value of $a_{i,j}$, the diagonal inverse is defined as $a_{j,i} = a_{i,j}^{-1}$. When all cells in the matrix were filled, the score of each criterion C_i is calculated as the geometrical mean of all values in the corresponding row i. This process was repeated for each respondent, obtaining the score of each criterion and sub-criteria. To calculate the overall score for each criterion or sub-criterion, the average over GM_i from each

respondent was calculated. As a result, this score aimed to reflect the collective assessment of the case company for the particular criteria or sub-criteria.

Table 3.3: Structure of pairwise comparison matrix for criteria and sub-criteria

	C_1	C_2	...	C_n	Criteria/Sub-criteria score
C_1	1	$a_{1,2}$	...	$a_{1,n}$	GM_1
C_2	$a_{2,1}$	1	...	$a_{2,n}$	GM_2
...	...	...	...	...	...
C_n	$a_{n,1}$	$a_{n,2}$	...	1	GM_n

All criteria and sub-criteria were evaluated based on the same method, however, sub-criteria with different parent criteria were not directly compared. As a result, the weights calculated in the previous step were the local weights. Local weights only described the relative importance compared to other sub-criteria with the same parent criteria. Therefore, the local weights needed to be converted into global weights to be compared against all other criteria. This was calculated as the local weight $w_{i,k}^{local}$ of sub-criteria $C_{i,k}$ multiplied by w_i^{parent} to get the global weight $w_{i,k}^{global}$, i being the index for number of parent criteria and k being number of sub-criteria for said parent.

3.6.3 Scoring and final score calculation of RE assessment methods

For each method, a score was given based on the fulfillment of each criterion and sub-criterion. In Table 3.4, the overall structure for RE method evaluation can be found. The rows consist of methods and criteria listed in columns, each accompanied by its respective global weight. Each empty matrix cell represents the score of a method for the matching criteria or sub-criteria. The scale employed in the study was binary, meaning that the method either fulfills or does not fulfill criteria, denoted as yes or no in the matrix. Fulfillment of criteria was given a score of 1, while the latter case was given a score of 0. The matrix was filled out and methods were given a score based on the scale defined. The final score of one method is defined as the sum product of the global weights and values of individual method columns. A higher score reflected better overall alignment with the company's priorities. The method with the highest score was then selected for the RE assessment.

3.6.4 Assessment design

The assessment was designed based on the case company priorities and weightings of the method evaluation and selection. Due to the best scoring method not covering all criteria, additional methods were to be implemented to complement the selected RE method. The assessment design also included the selection of indicators based on available data and the selection of temporal resolution for the data set.

Table 3.4: Structure of method evaluation and selection matrix

Criteria		Global weight	Method 1	Method 2	Method 3	Method 4	Method 5	Method 6
C_1	Sub-criterion 1	$w_{1,1}$						
	...	...	...	...	...	...	...	...
	Sub-criterion N	$w_{1,N}$						
...	...	...	...	...	...	...	...	...
C_n	Sub-criterion 1	$w_{n,1}$						
	...	...	...	...	...	...	...	...
	Sub-criterion N	$w_{n,N}$						
Final score								

3.7 Execution of assessment

The execution of the assessment was done based on the assessment design, data collected, and the results of data visualization in the previous stages, and calculations were performed only for the pilot area. Before calculations, it was necessary to prepare the data, which involved selecting, cleaning, constructing, integrating, and formatting (Chapman, 2000). Following the data preparation, the indicators were calculated. The main goal of the assessment was to quantify KPIs that are capable of showing not only environmental performance but also opportunities for improving the process. Regarding what graphics, statistics, and information to report, these were defined based on the qualitative study.

4

Results of manufacturing system analysis

4.1 Observation

4.1.1 Pilot area

The pilot area selected for this study case was the machining line section, and it was chosen based on the case company's interest regarding the energy consumption of this section. The machining line is an area inside the plant that produces cylinder blocks the whole year round. It is a set of multiple machines and different subsystems (ventilation, lightning, pumping, etc.) specialized in material removal. It has as input cast iron blocks that go under multiple machining processes (drilling, turning, and milling), performed in a set of linear steps. There are other necessary machines, such as washing, drying, and assembly of components. It has more than 20 stations, which can be divided into automatic, semi-automatic, and manual. Additionally, it counts with systems to carry the blocks automatically from one machine to the other, a system called Hidromation that provides cutting fluid and water to all the machines, an evacuation system for the remaining metal chips, and a preset room in which all the parameters for cutting are set. A picture of a small portion of this section can be seen in Figure 4.1.

Due to the high energy consumption the machining line has shown over the years, managers, engineers, directors, and technicians have applied different measurements to reduce it. One example of this is the replacement of the motors of the machines due to their long age, which took a lot of years to finish and was done by the year 2023. This shows how complex the system is and how committed employees are to the plant's performance. Their effectiveness in production has made them cataloged as a world-class manufacturing plant, achieving an overall line effectiveness of more than 85% for their machining line section.

Additionally, the plant is not only committed to performance but also to sustainable production. By using an environmental management system (EMS) approved by ISO14001, combined with a cost deployment methodology to have a full understanding of cost inefficiencies, they have been able to reduce the environmental

Figure 4.1: Photograph taken of a small portion of the machining line

footprint to a great extent. As part of their achievements, they have become a zero-waste, use 100% renewable energy, and landfill-free plant, using recycling and incineration as their only methods for waste management, recovering energy in the process. Besides this, they have implemented a closed-loop water system, meaning that they reuse all the water they need for everyday production.

To be able to monitor both production and environmental performance, they use a combination of manual data gathering and automatic data gathering. This means that they combine both systems that collect, store, and transform data into valuable information automatically, and protocols to either install or use already implemented sensors to manually record data in individual spreadsheets. These make the company able to track resource consumption, production aspects (e.g. Processing time, idle time, A.P.Q. losses, equipment errors, etc.), and resource losses with great detail.

4.1.2 System Boundary

The system boundary specifies all the elements that are considered in the assessment, along with the flows of the system (inputs and outputs). In this context, the machines situated inside the production area are the most relevant elements, and because of that, they were the only elements included in the assessment. In total, 24 stations were analyzed, and they can be divided into: CNC machines, washing machines, drying machines, deburring machines, inspection stations, and assembly stations.

The inputs of the system were classified into material and energy inputs. Based on the work of Pervaiz et al., 2020, the main inputs to take into consideration when analyzing the machining process in the study case are: cylinder blocks, water, compressed air, and fluid and solid material supplies (chemicals and consumables). Combined with energy, these summarize all the main resources that enter the system.

As outputs for the system boundary, it only counts as finished cylinder blocks, water, and waste (contaminated chemicals, and metallic chips).

4.2 Qualitative analysis

4.2.1 Process mapping and data inventory

To understand the complexity of the machining line, and the data available, IDEF0 two process maps are drawn for two hierarchical levels separated into two. Based on these, and meetings with the machining line experts on the collected data, the data inventory was created. As it is possible to see in figure 4.2, at this level, only the data of two flows were available and could be allocated to the cylinder blocks production level. Although data is collected for other flows, it is aggregated for the whole building in which the machining line and other production areas share. As a result, it is difficult to know what part of said data that can be allocated to the machining line. This is the reason why they are not labeled as the green category.

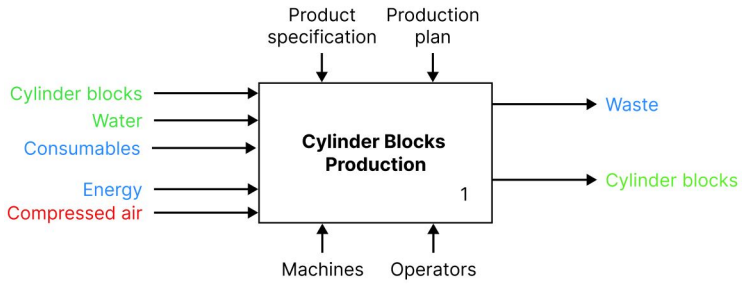

Figure 4.2: Process map of the machining line (Level 1)

Based on the first map, the second map describes the main processes performed by the stations mentioned above. In total, four main processes are necessary to execute to produce cylinder blocks (machining, assembly, washing, and drying), plus an additional preparation process called "preset". This can be seen in Figure 4.3, in which the block enters the system in the machining process and exists in the system in the drying process. For the particular process of machining and assembly, some resources (tools and lubricating chemicals) are provided from preset.

According to these two figures, it is possible to see how the availability of data changes for different levels of detail. Due to this, Figure 4.4 was created to summarize all gathered data that can be used for the assessment. In this, it is possible to see the three dimensions that describe the characteristics of the data: temporal resolution (or sampling rate), level of detail, and extension. The "X" symbol was used whenever the data was available with that particular aspect of the dimension, and the "O" symbol was used whenever it was possible to calculate that aspect of the dimensions. For example, cylinder blocks produced were found to be available per month, which can be aggregated to calculate the annual value. This table was adapted from the

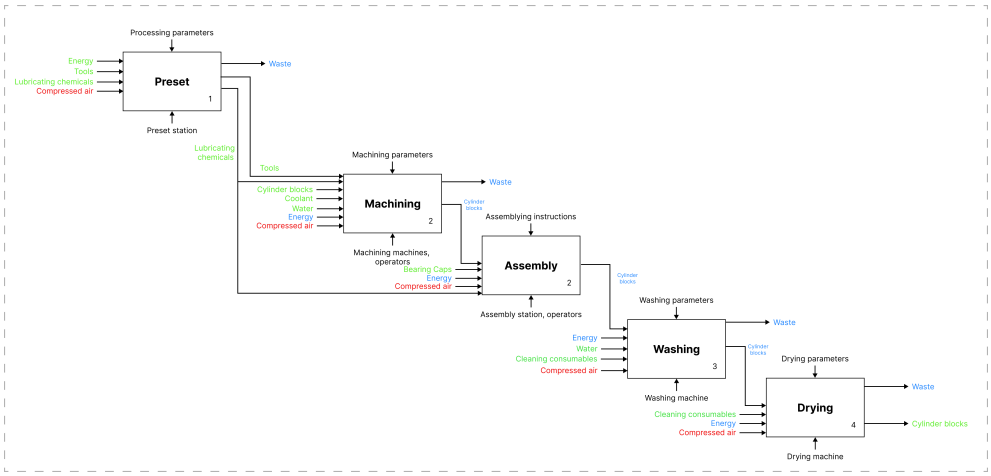

Figure 4.3: Process map of the machining line (Level 2)

work of Fang et al., 2023, in which the temporal resolution was the only dimension counted. The other two were added after analyzing the data the employees have collected. To understand what was collected, a description of the meaning of each resource is made:

TEMPORAL RESOLUTION									
	Material	Energy			Water		Waste	Chemicals and consumables		
	Cylinder Blocks	Electricity			Water		Metal chips	Tools	Coolant	Other Chemicals
Monthly	X	X		X	X		X		X	X
Semi-annual	O	O		O	O		O	X	O	O
Annual	O	X	O	O	X	O	O	O	O	O
LEVEL OF DETAIL										
Machine-level		X		X	X			X		
Group of machines-level		O		O	X			O		
Cylinder block production-level	X	O	X	X	X	O	X	O	X	X
EXTENSION										
2020	X				X			X	X	X
2021	X	X			X			X	X	X
2022	X	X		X	X		X	X	X	X
2023	X	X		X	X		X	X	X	X
* Same color indicates what years cover the data for that temporal resolution										

Figure 4.4: Summary of the availability of data based on its different dimensions

- **Material**: It refers to the workpiece material that enters the system to be machined, which is the casted cylinder block. This product is transformed after going through the machining line. Because of that, it was assumed that the raw cylinder blocks were equal to the amount of finished cylinder blocks. Due to the necessity of the machining line to quickly adjust the production to the demand, the number of blocks produced per day is tracked and reported daily. However, since no other resource has this temporal resolution, it was not included in the table.
- **Energy**: Energy refers to the power consumed to machine, assembly, clean and dry cylinder blocks. Due to its complexity, for this particular resource, colors are used to describe how the data is presented. While power data were collected monthly taking direct measurements from the power station in kWh (orange color), there are measurements of consumption per machine in kWh/h (color blue). This means that while the power station measurements are already in

the desired units, the machine measurements need to be transformed to be able to calculate the power in the same units. Additionally, for just a few machines, power is being measured monthly together with the power station measurements, represented with a small orange cell at the machine level.

- **Water**: It refers to the water consumed by the processes of machining and washing. Similar to energy, some additional colors are used to explain the data. The green color is for data reported annually for the cylinder block production level, and the purple data is for data that is reported monthly for different groups of machines and individual machines. There are four sources of water consumption in the machining line (grouped according to the four water meters installed): manual testing consumption, washing machine consumption, consumption of the special machine OP60, and consumption of all the remaining machining machines together.
- **Chemicals and consumables**: It refers to all the purchased products that need to be used constantly to run the machining line. For this particular data, it was found to be more than 30 different types of chemicals reported (e.g. lubricating oil, hydraulic oil, instant adhesive, etc.) plus the tools that are bought for the machining machines. Since chemical data was found too extensive to be handled in separate variables, it was decided to be grouped into two categories: coolant (also referred to as Quakercool) and other chemicals. The main reason is that the coolant represents 70% of total chemical consumption on average, with some months being higher than 90%.
- **Waste**: It refers to all metallic chips that are generated from the metal-removing processes, along with all other used consumables that are generated after production (e.g. plastic scrap for packaging, wood, worn tools, etc.). However, since all other waste different than metallic chips is added to one monthly report for the entire building in which the machining line is located, it is difficult to tell what can be allocated to the machining line. Therefore, only metallic chips were used for the analysis.

4.2.2 Resource flow mapping of pilot area

The resource flow mapping of the machining line includes the flow of all resources along with the actual layout of the production area. This chapter will present the mapping of one layer at a time, each highlighting one or a few resource flows. In total, it was decided to show four layers of resources: material flow layer, electricity layer, coolant and water layer, and compressed air layer.

First layer: Machines, conveyors and material flow

Figure 4.5 illustrates the first layer with machines, positioning of conveyors, and cylinder block flow, including all machines inside the machining line system boundary. For transportation of the cylinder blocks, there is an automated system of

conveyor belts for linear movement and gantry loaders for transport in the vertical and horizontal axes. As it can be seen, although the arrangement of machines seems like they are loops and parallel processes in the system, all the processes are executed in series. Although it is not shown here, to be able to adapt the machining line to the production demand, they have a series of buffers in which the cylinders will wait after finishing one process and before going into the other.

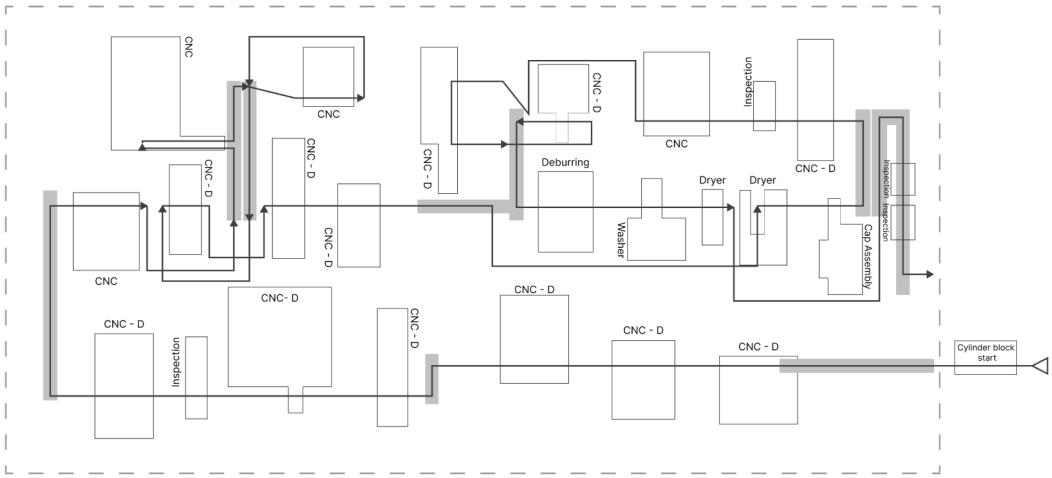

Figure 4.5: Resource flow mapping, first layer with cylinder block flow and processes with labels.

Second layer: Electricity Layer

The second layer, which can be seen in Figure 4.6 shows how the electrical supply system provides energy for every machine. Although there are other sub-systems that the system supplies (such as conveyors, gantry loaders, lighting, water pumping system, air pumping system, etc.) these are not included since they are not part of the system boundary.

Third layer: Waste, water, and coolant layer

The flow map of the waste, water, and coolant layer in Figure 4.7 shows both inputs and outputs. Regarding the inputs, it is possible to see to which machines are the mix of coolant and processed water being supplied (blue color lines). The system that provides the coolant and process water to the production area is called Hidromation. This system is where coolant and process water are mixed and pumped out to the machining line. Regarding outputs, purple arrows show the metal chips waste, which are metal scraps produced from machining processes. This means that, after the coolant has been applied to the cylinder block, it carries out the metal chips to an evacuation system. The weight of metal chip waste measured by the company also includes an additional percentage of cutting fluid and the company does not have any means to separate them. However, the weight that the cutting fluid adds is negligible. The other chemicals are not included in the mapping due to

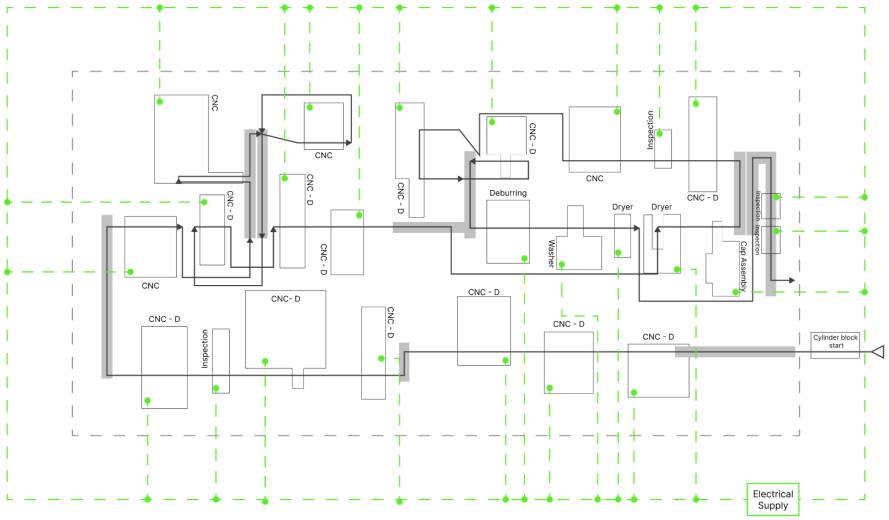

Figure 4.6: Resource flow mapping with electricity layer.

various reasons. The high number of chemicals included and the inconsistent use of said chemicals make it difficult to add and attribute to processes in the production area. Coolant is consistently utilized in terms of time frame and application in the machining line compared to other chemicals that differ yearly.

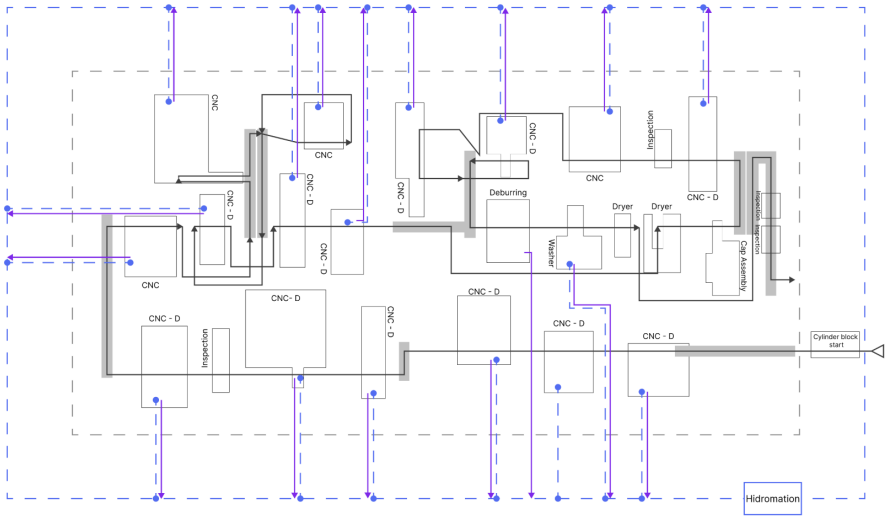

Figure 4.7: Resource flow mapping layer with Coolant (process water and chemicals) and metal chip waste.

Fourth layer: Compressed air

The fourth layer in Figure 4.8 shows the flow and allocation of compressed air. Compressed air is supplied to every machine and is essential for the hydraulic parts of processes. It is an important resource that uses a part of the electrical energy of the whole electric supply system. Unfortunately, the plant does not have the means to

collect data regarding compressed air consumption. Therefore, this resource cannot be considered in the assessment.

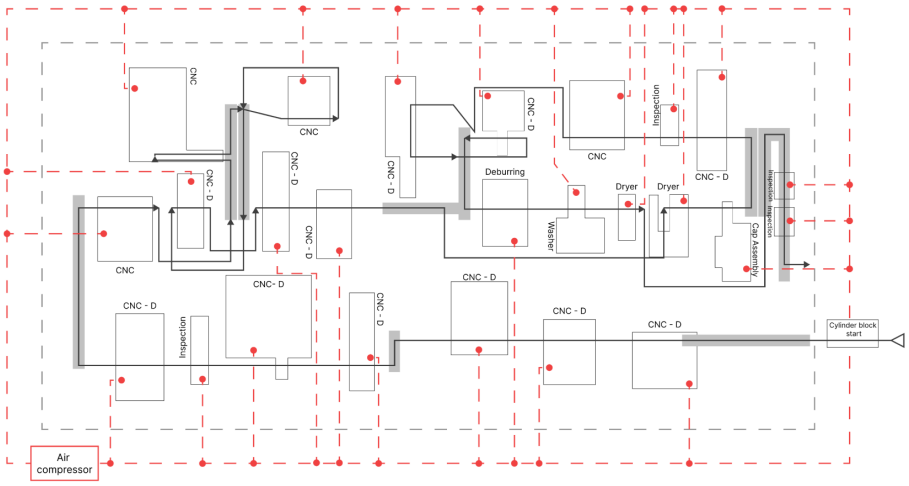

Figure 4.8: Resource flow mapping layer with compressed air

4.2.3 Data quality assessment

The data quality assessment was performed for each resource identified in the resource flow mapping, analyzing the following dimensions: Availability, Usability, Reliability, Relevance, and presentation quality. These dimensions were evaluated using the following data requirements: data needs to be measured over time and allocated to either the machining line or to individual processes in the machining line. Only two requirements were created to allow flexibility in the usage of data provided by the company.

- **Material**: About availability, quantity of production is recorded in spreadsheets, providing an easy interface to access it, and receiving daily updates, fulfilling the elements of accessibility and timeliness. Besides, it meets the element of authorization since they have the right to use the data. Regarding usability, it is fair to say that data come from a specialized organization, ensuring transparency since they need to report the blocks accurately to sell them, fulfilling credibility. Apart from this, a clear label is provided to define the data, fulfilling the definition element. In this case, because there is no other data that shares terminology with this data, the metadata element of the framework does not apply. In the case of reliability, although data was found to be accurate, integral, and complete, there were problems regarding consistency. This was because it was found in other files that also showed the values of cylinder blocks produced that these were slightly different from the ones in the main file. Regarding the auditability element, possible auditors can evaluate data accuracy and integrity fairly. In the dimension of relevance, the dataset retrieved matches the need of the assessment since it was production-level data. For the presentation quality element, the data was clear and easy

to read, meeting the needs of the assessment the way it was provided. Finally, it was not difficult to structure the data through technology for this project, which fulfills the requirement of structure.

- **Energy**: About availability, energy data is spread through multiple spreadsheets, providing an easy interface to interact with. Some of the files receive regular updates (monthly), while others are updated only when needed, which means that does not fulfill the aspect of timeliness. Regarding usability, although some data was estimated, it comes from experts, which fulfills the aspect of credibility. The aspect that does not fulfill is definition, since the lack of additional descriptions makes the files difficult to understand. For the case of metadata, while the terminology is shared with other files, the difference in what is being measured is clear, fulfilling the metadata element. In the case of reliability, although data was found to be accurate and integral, there were problems with consistency (different units), and completeness (data missing for some months). Besides this, in the dimension of relevance, the dataset retrieved partially matches the needs of the assessment, mainly because it lacks measurements of individual machines. Finally, regarding presentation quality, for some files, data was unclear, with a lack of descriptions and abbreviations to facilitate the understanding, which does not fulfill readability. Regarding structure, it was not difficult to structure the data through technology for this project.
- **Water**: About availability, water was recorded in one spreadsheet, providing an easy interface to access it read it, and receive monthly updates. This means that water data fulfill both accessibility and timeliness. Regarding usability, credibility, definition, and metadata are fulfilled as the data is measured by experts. It presents simple labels that are easy to understand and does not share terminology with other datasets. For reliability, the data was accurate, consistent, integral, and complete. Regarding the auditability element, integrity, and data accuracy can be evaluated by auditors easily since they have an automated data collection system. In the dimension of relevance, the dataset partially fulfills the assessment dimension because it also lacks information for some machines. In general, it is of high data quality since data can be explained in well-known terms (e.g. consumption, hydrometer). Regarding structure, it was not difficult to structure the data through technology for this project.
- **Waste**: About availability, it receives monthly updates and provides an easy interface to access, fulfilling accessibility and timeliness. Regarding usability, it is fair to say that data come from experts, it does not share terminology with other files, and the descriptions it provides are clear, fulfilling credibility, metadata, and definition. In the case of reliability, data was found to be accurate, consistent, integral, and complete. Audibility is difficult to evaluate since there are several types of waste in the same file, meaning it can take a lot of time to evaluate the accuracy and integrity. In the dimension of relevance,

only a small portion (metal chip waste) is relevant for the assessment but does not fulfill the requirement. In general, it is good quality data, but it has one issue in presentation quality. It was necessary to ask the plant which type of waste was allocated to the machining line (metal chip waste) since the file did not explain this. Regarding structure, it was found that it is also not difficult to structure the data through technology for this project.

- **Chemicals and consumables**:

  Regarding chemicals, in terms of availability, the data is updated monthly and is easy to access. Regarding usability, credibility, and metadata data are fulfilled, but not definition since the labels make it hard to know what chemicals are used for machining. In terms of reliability, chemical data was found to be integral, and complete. However, problems were found regarding accuracy and consistency. One thing to notice is that collected chemical data (coolant) is based on audits of the amount requested from the company warehouse. Because of that, it is difficult to estimate how much of the requested is related to consumption. Not only that but also the rate of replacement is unknown because it depends on the method used (Fuchs, 2024). Additionally, auditability is compromised since there are several different types of chemicals, which could make it difficult to evaluate the integrity and accuracy of all. Regarding presentation quality, it meets both readability and structure. In the case of tools data, although it can be easily accessed, timeliness is compromised since they update everything by semester. Consistency was compromised since they did estimations for some portion of the data, rather than collection. Apart from that, completeness is also compromised since for one of the years, the values were not recorded over time. This also creates problems with audibility, since it could be difficult to evaluate integrity and accuracy. Regarding the dimension of relevance, the time interval makes it not fulfill this requirement. Finally, for presentation quality, the data is clear and understandable, their descriptions are concise, and it is not difficult to structure the data.

- **Additional production data:** The data refer to the processing time and APQ time for all machines in the machining line. About availability, it receives hourly updates since it is handled by an automatic monitoring system, and it is easy to access for visualization. However, transformations are needed to aggregate data into one single data set and be integrated with other resource consumption data, which makes data not fulfill structure. For usability, since it is measured by the monitoring system, it can be said that they are reported by a specialist, which makes them credible. Apart from that, it meets the aspect of metadata and definition. In the case of reliability, data was found to be accurate, consistent, integral, and complete. Since the system of the collection of this data is automated, audits are probably not difficult, fulfilling auditability. Regarding the dimension of relevance, data meets requirements, which makes it suitable for the assessment. Due to transformation, it needed to be manually extracted via spreadsheets (60 in total), then processed (ag-

gregation and restructure), and integrated to match the temporal resolution with other data. For presentation quality, the data was not easy to read and lacked descriptions while existing labels were misleading and with the risk of interpretation error.

To summarize this data quality assessment, a figure was created:

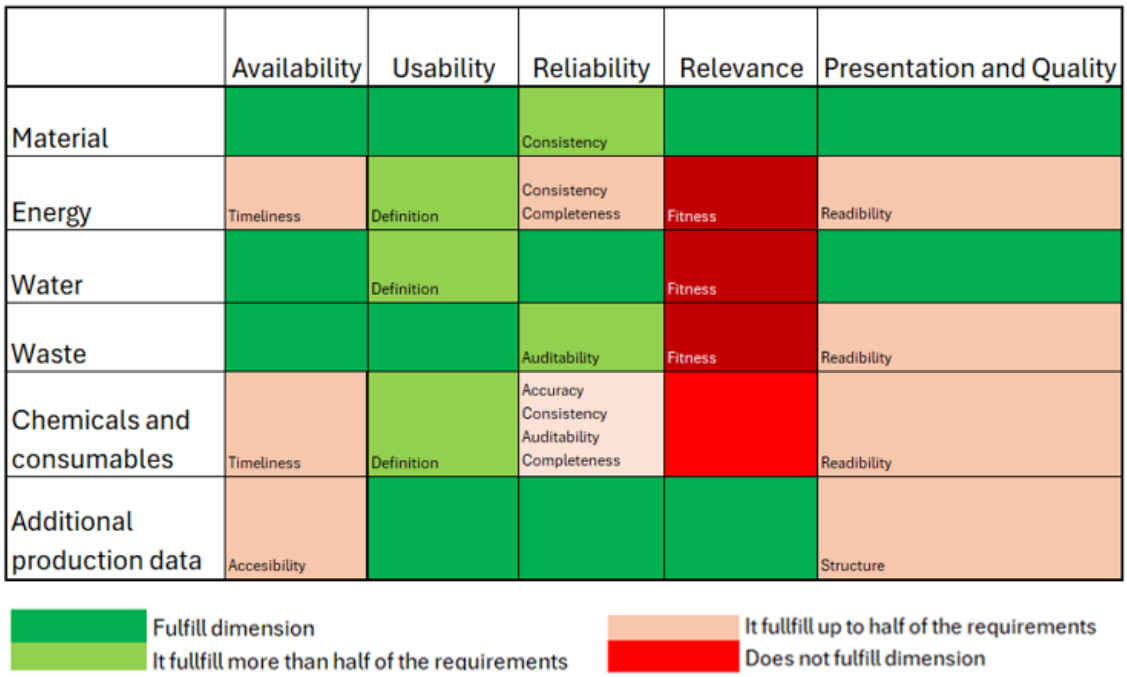

Figure 4.9: Data Quality Assessment

As it is possible to see, for the data to fulfill the whole dimension, it needs to fulfill all the requirements or elements in that dimension. To show this, for all the cells that are colored dark green, the elements that were not fulfilled are listed. Overall, this result highlights how relevance was a dimension that was not fulfilled for several resources. By ensuring this dimension, it could have been possible to calculate more indicators and potentially implement another type of assessment.

4.3 Data understanding

4.3.1 Evolution of resource consumption over time

The graph in Figure 4.10 includes all data points of resource consumption for each month of the year 2020 to 2023. Tools were not included in the visualization due to the semi-annual temporal resolution. Not all data could be collected for the specific years, as water only includes data for 2023, energy has data from 2021 to 2023, and chips only have data recorded for 2022 and 2023. As a result, only the year 2023 has data recorded for all resources. Most resource consumption, except for Quakercool, follows the trend of blocks produced, increasing and decreasing

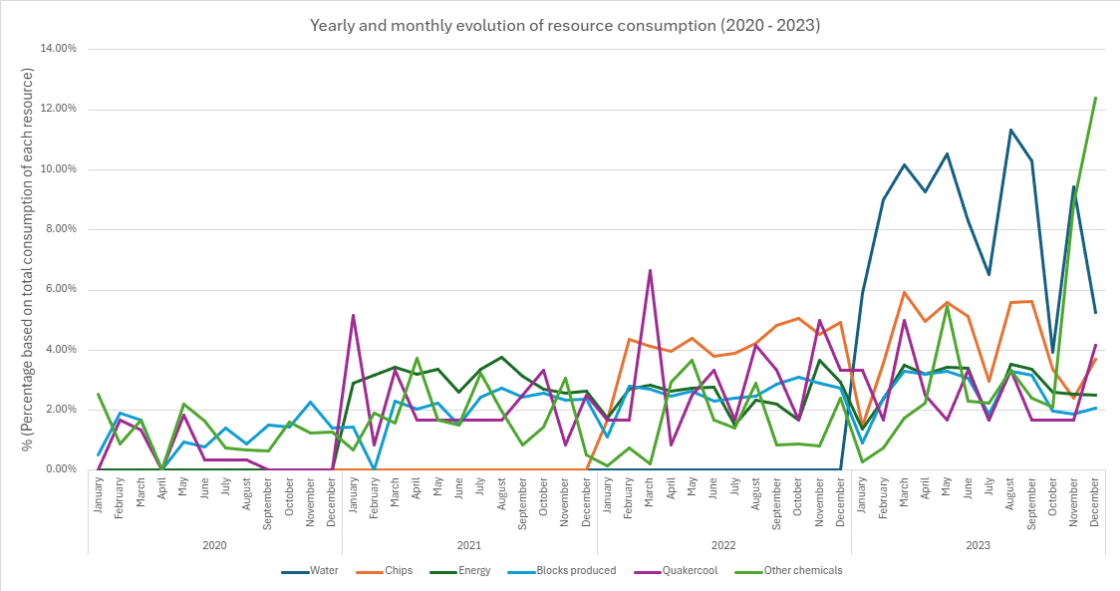

Figure 4.10: Yearly and monthly evolution of resource consumption

accordingly. This is especially apparent when comparing chips and the number of blocks produced which can be attributed to the functional dependencies regarding the consumption of resources and the number of blocks produced. Energy generally follows the trend of blocks produced, especially in 2023. However, data points of water and energy show irregular behavior in 2023. When examining the water curve from October to December of 2023. It increases significantly in November followed by a significant decrease in December despite the smaller relative change in blocks produced. The other chemicals show similar behavior of mostly following the trend of blocks produced with irregular changes. However, the trend of Quakercool does not match any other variable, and its changes across every year and corresponding months show no regular pattern. This is strange considering how the machining line utilizes Quakercool where consumption should show some correlation between blocks produced and water.

The year 2023 has the highest relative consumption for all resources except for blocks produced, Quakercool, and other chemicals. Especially in 2020, which can be due to the pandemic. This can be seen as 2020 shows the lowest recorded values with a stable increase until 2023. Also, data on blocks produced, Quakercool, and other chemicals was not recorded in April 2020, which is the official start of the pandemic. Based on the visualization, there are trends and patterns of consumption in which some resources follow. The behavior of resource consumption occasionally deviates from the trend showing that there could be underlying reasons in production causing this.

5

Results of resource efficiency method selection

5.1 List of collected resource efficiency method

After analyzing all the relevant articles, eight methods were found to perform the RE Assessment. The Table 5.1 summarizes the characteristics of these methods:

Table 5.1: Summary of the methods found. W=Water; M=Material; E=Energy; L=Land; C=Cost; Ws=Waste.

Method	Coverage						Driving factor	Quantifies environmental impact
	W	M	E	L	C	Ws		
MFCA (Schmidt & Nakajima, 2013)	X	X	X		X	X	Financial	No
MFA (Dunuwila et al., 2018a)	X	X				X	Both	Yes
RVM (Papetti et al., 2019)	X	X	X		X		Both	No
EMS-CD (Jaouad Abisourour & Farchi, 2021)	X	X	X		X		Both	No
VSM (Ismail et al., 2019; Papetti et al., 2019)	X	X	X		X	X	Both	Yes
REC & REF (Lundholm et al., 2012b)	X	X	X		X		Both	No
LCA (Baumann & Tillman, 2004)	X	X	X	X		X	Environmental	Yes
MLR (Dehning et al., 2017)			X				Environmental	No

Out of the eight methods, most of them count the environmental aspect. However, as it is possible to see, in only three of them the environmental impact was calculated.

5.1.1 Resource Value Mapping

Resource Value Mapping (RVM) is a method introduced by Papetti et al., 2019 with a case study that maps and categorizes resource consumption based on lean principles as value-added (VA), non-value-added (NVA), and waste (W). Value-adding means activities that create value that customers are willing to pay for.

Non-value-adding refers to activities that do not directly contribute value, such as the ramp-up time of a machine. Waste refers to activities that do not add any value. The mapping and classification are compiled into a single graph in such a way that aims to eliminate infobesity while enabling analysis at multiple hierarchical levels of production processes. There are two additional efficiency indicators to identify criticalities in production. The first component consists of production flow mapping with the plant layout, and the second is the process box highlighting process-specific characteristics (Papetti et al., 2019) shown in Figure 5.1. The process box used for visualization shows the consumption of all resources for a given process with a color-coded section to highlight the contribution of each consumption category.

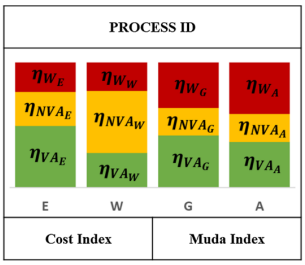

Figure 5.1: Process box with consumption of each resource, classification of consumption, Cost and Muda Indices (Papetti et al., 2019).

5.1.2 Material Flow Analysis

Material flow analysis (MFA) is a systematic method that assesses all the material inputs and outputs of different processes from a production system. It can be done at multiple levels (process level, production level, factory level) and is defined in a specific space moment in time (Dunuwila et al., 2018a). It quantifies all the mass flows of materials, based on the mass balance principle: input mass (materials to be consumed) and output mass (materials/products produced, emissions, and waste) must be equal. To perform the assessment, it is necessary to extract data regarding all the mass exchanges in the system. This is collected for relevant processes and subsequently, it is then visualized in a flow diagram. To handle uncertainties regarding data, software tools can be used.

An example of this type of diagram can be seen in Figure 5.2. This shows an MFA performed for a crepe rubber manufacturing system, and it presents in detail all the resources used in different factories with the same processes. As it is possible to see, it shows the scale of consumption of each resource by changing the size of the flows according to its value, which is the strength of the method. MFA highlights the resources being consumed the most and also the waste that is produced the most, something that can tell the company where to locate its efforts to optimize resource consumption and waste production.

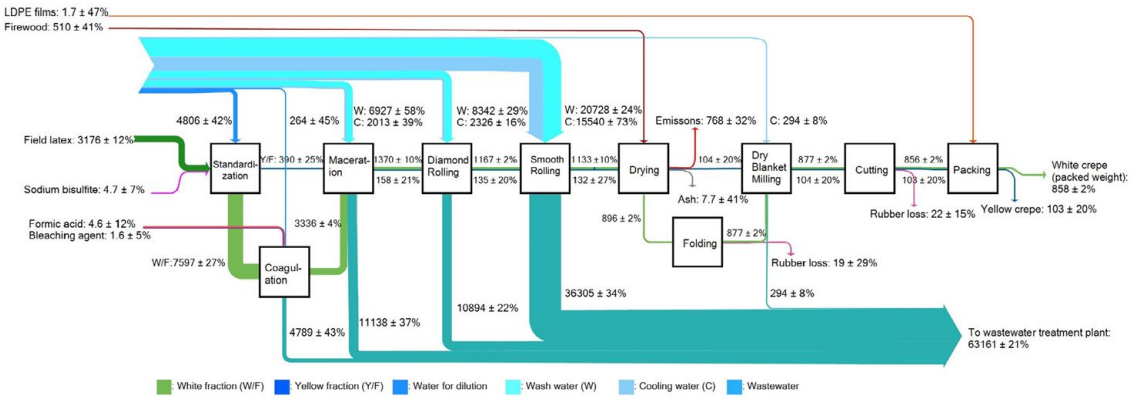

Figure 5.2: Material Flow Analysis diagram of a crepe rubber manufacturing system (Dunuwila et al., 2018a)

5.1.3 Material Flow Cost Accounting

Material flow cost accounting (MFCA) is a method that follows similar principles to MFA. The main difference is that MFCA transforms all the inputs and outputs of resources and waste into cost. Based on this, it can be seen which flows are the most expensive to the company, and which processes produce the most critical amount of waste in terms of money. Because of that, not only the costs of acquiring the material are the ones that are implemented in the diagram, but everything that is spent to execute the processes (e.g. cost of machines, cost of labor, cost of energy, cost of tools, etc.).

5.1.4 EMS-CD

Environmental Management System - Cost Deployment (EMS-CD) is a method proposed by Jaouad Abisourour and Farchi, 2021 to connect environmental benefits from adhering to the framework of ISO 14001 and financial aspects with Cost Deployment. ISO 14001 is an international standard that outlines the conditions for an efficient Environmental Management System (EMS). Cost deployment (CD) enables the quantification of losses at a process level, focuses on improvement actions, and establishes action plans. To do this, the causes of losses need to be identified.

The identification of losses is obtained by collecting manufacturing data to know the current state of production and identification, classification, and evaluation of losses. From the information regarding the state of production, the aim is to identify all waste or losses in the chain of processes. Furthermore, Jaouad Abisourour and Farchi, 2021 presents five categories for processing costs: Labour and outsourcing costs, machinery, materials, utility costs (e.g. energy, water, compressed air), and external service costs. The losses are classified as Considerable, Significant, or moderate based on the impact.

The next step is to classify losses as causal losses and resulting losses. Causal losses

are losses caused by a process or machine. It could be due to events such as machine breakdown or parameter settings. All causal losses are categorized as Considerable or Significant. Resulting losses occur as a byproduct of causal losses. To exemplify the relation between processes, causal losses, and resulting losses, consider a CNC machine as a process in production. A causal loss caused by the process can be idle time. The resulting loss will be overconsumption of electrical energy quantified as kWh. All losses are then evaluated and converted into the same unit of measurement, currency (Jaouad Abisourour & Farchi, 2021). The benefits of this method are the aspects of localizing, categorizing, and comparing the losses.

5.1.5 Value Stream Mapping

Value Stream Mapping (VSM) helps visually identify the origins of waste in production. It accomplishes this by graphically showing inventory flows and providing additional information with arrows, symbols, and metrics. In the VSM the process flow is shown to identify and solve bottleneck cycle time against Takt time, number of inventory, lead time, waiting time, and process time. In short, VSM can be used to map the current state of production and improve different aspects of production, such as lead time, cycle time, etc. The literature describes two steps necessary for proper visualization of flow and information related to production (Ismail et al., 2019):

- Draw mapping of the current state of production. This is to identify sources of waste and classify activities as VA or NVA.
- Draw mapping of the future state of production based on improvement plan

There are multiple benefits of the methods for the study. It can visually present the inventory flows and classification of activities according to lean philosophy, aiding analysis of waste sources and identifying potential improvements. Resource value mapping categorizes the resource usage in every process allowing the identification of problematic processes. However, it does not help identify specific information of causes within the process itself. This is the benefit of VSM concerning analytical benefits. It is not difficult to utilize the tool due to the visual aspects which can relieve information sharing and overall understanding. However, VSM is only an analytical tool that identifies the origins of causes of issues in the value chain and does not eliminate them. Despite compiling information in a single graph, the graph can be visually overwhelming for large value chains (Ismail et al., 2019). The method has many variations which extend the analysis to handle various dimensions. As a result, the general method VSM has high adaptability and can be applied to many scenarios.

Energy Value Stream Mapping

EVSM is an extension of VSM but adds energy as a dimension of analysis. The drawing of the state of production adds energy as a subject of observation for the

processes. A study also introduces and observes the dual energy signature of processes to categorize activities as VA or NVA. Separate energy graphs of processing with and without a workpiece are constructed and combined to create the dual energy signature. These discrepancies based on data behavior aid in differentiating activities (Schillig et al., 2013).

Green Value Stream Mapping

Green Value Stream Mapping (G-VSM) is an additional extension of the VSM family, focusing on evaluating Green Productivity. To do this, G-VSM includes the Green Productivity Index (GPI) and is calculated as the economic indicator divided by environmental impact (EI). The economic indicator is calculated as the ratio of revenue (value-added output) divided by the total cost (resource input). In other words, the economic indicator describes the efficiency of resource usage in terms of currency. Another differentiating aspect is that G-VSM defines waste as excessive use of energy, water, material, waste, transport, emissions, and damage to biodiversity (Marimin et al., 2014).

Sustainable Value Stream Mapping

Sustainable Value Stream Mapping (Sus-VSM) addresses environmental and societal aspects that the conventional VSM lacks. Sus-VSM was implemented in a case study by Faulkner and Badurdeen, 2014 to develop a methodology for evaluating economic, environmental, and social sustainability performance in manufacturing systems. The case study implements multiple indicators to address the mentioned topics. Indicators such as GHG emissions, the ratio of renewable energy, overall energy consumption, value-added and non-value-added consumption, and various cost indicators (labor, consumables, etc.) were included (Faulkner & Badurdeen, 2014).

5.1.6 RE cockpit and flowchart

The paper introduces a resource efficiency assessment system consisting of the Resource Efficiency Cockpit (REC) and Resource Efficiency Flowchart (REF). REC measures resource efficiency using key performance indicators (KPIs) and visualizes data in radar charts, allowing for tracking and improvement of production efficiency. REF analyzes efficiency losses and their economic impact through bar charts, categorizing losses as direct or indirect. The paper outlines three eco-efficiency objectives: reducing resource consumption, reducing environmental impact, and increasing the value of used resources. It also provides an enhanced definition of waste for resource efficiency, emphasizing non-value-adding activities, unnecessary resource use, and non-recoverable waste. While the system offers clear visualization and includes material and energy consumption, it is mainly suited for small and medium-sized enterprises (SMEs) and lacks a specific focus on water and chemicals. The combination of indicators and loss identification in graphical form helps to analyze results

and create improvement plans. However, further adaptation is needed to address lower hierarchy levels and evaluate environmental impacts as the method does not include this aspect (Lundholm et al., 2012b).

5.1.7 Multiple Linear Regression

The paper presents a statistical method using a multiple linear regression (MLR) model to analyze energy intensity in automotive production, with a case study demonstrating its application. This general method can be applied to other production plants and involves several steps: selecting influencing factors, gathering data, analyzing simple correlations with Pearson's r, formulating the MLR model, and testing the model. Initially, relevant factors like production volume, utilization rate, and facility temperature are identified through data sources and stakeholder input. Comprehensive data is then gathered, ensuring completeness. Pearson's r measures linear correlations between pairs of factors, but MLR is used for multivariate analysis, facilitated by tools in MATLAB and Python. Statistical quality is assessed using metrics such as RMS and R^2. The model is tested with training and real data. This can be done from separate datasets or by splitting a single dataset (Dehning et al., 2017).

5.1.8 Life Cycle Assessment

Life Cycle Assessment (LCA) analyzes a product's life cycle in four steps: mapping mass and energy flows, creating a life cycle inventory, conducting a life cycle impact analysis (LCIA) to convert waste and emissions into environmental impacts, and performing additional analyses and interpreting results. Combining LCA with other methods typically involves only steps 3 and 4. LCA classifies waste into specific environmental impacts, is easy to understand, and requires basic statistical knowledge. However, it ignores production parameters, requires hard-to-find data, and excludes economic aspects. Despite these drawbacks, with the correct data, implementing LCA is straightforward and effective for calculating environmental impacts, especially in the automotive sector where impact categories are well-defined (Baumann & Tillman, 2004).

5.2 Evaluation of case company priorities and RE method selection

To evaluate the priorities of the company, criteria were generated based on expert meetings, studies that include a matrix for selection of RE assessment methods (Jasiński et al., 2021, Weyand et al., 2023, and Papetti et al., 2019), and the most important characteristics of the methods described in the literature review. The purpose was to collect these characteristics of the assessment and create criteria by which respondents could evaluate their importance against others. These can be

summarized in Table 5.2, which contains the following five criteria:

- **Flow maps**: Flow maps are a common element in resource efficiency assessments. They can be found in methods such as material flow analysis (Dunuwila et al., 2018a), material flow cost accounting (Schmidt & Nakajima, 2013), and life-cycle assessment (Baumann & Tillman, 2004), and the value they provide is a visualization of the system boundary, allocation of the inputs and outputs to the right process, among others. For the methods that include flow maps based on the material flow analysis, the value also lies in the visualization of the volume of the inputs and outputs.
- **RE Indicators**: RE Indicators are the most important aspect of RE assessment. All methods have at least one type of indicator that can show efficiency. For example, material efficiency can be calculated in some of these methods, as the ratio of the final product's weight divided by the weight of raw material (Lundholm et al., 2012a). Other examples are positive product cost and negative product cost (Dunuwila et al., 2018b), and cost index for identification of critical processes in terms of resource consumption (Papetti et al., 2019).
- **Adaptability**: Adaptability is an aspect that can be seen from multiple perspectives. Based on the study of (Weyand et al., 2023), to select a RE assessment, time effort execution, time effort for initial skill adoption training, costs for data acquisition, and cost for evaluation and visualization are also relevant factors to consider. All these can reflect how adaptable the method is to the study case. However, since evaluating these costs is out of the scope of the project, and the characteristics of data and the possibility of assessing resource efficiency with that data is the main focus, the adaptability aspect was divided into two sub-criteria: can be done with collected data, and can be done with tools and software company already have.
- **Environmental Indicators**: Environmental indicators are key to understanding the environmental impact of manufacturing processes, and how sustainable they are. These can be selected depending on the type of process based on policies like the EU taxonomy (European Commission, 2023), national or international standards (Joung et al., 2023), or well-known methods like the ReCiPe model in LCA (Baumann & Tillman, 2004). Based on the particular process of machining (Pervaiz et al., 2020) and the extensive effort the plant makes to manage waste so it does not end up either on water sources or on land, it is concluded that the most relevant indicators are the ones that indicate resources depletion and GHG emissions.
- **Correlation of consumption and production**: The correlation between consumption and production refers to the possibility of linking resource consumption to relevant production aspects. Based on the process of machining (Pervaiz et al., 2020), relevant production factors that can be linked to consumption are IDLE power (power machine consumes while waiting for a workpiece), cutting power (power machine consumes removing material from the

workpiece), tool utilization (rate of replacement of tools), production volume (blocks finished per unit of time), weight, hardness, surface texture, feed rate, spindle speed, depth of cut, and material removal rate.

From the results of the survey regarding company priority of these criteria, these were the results found:

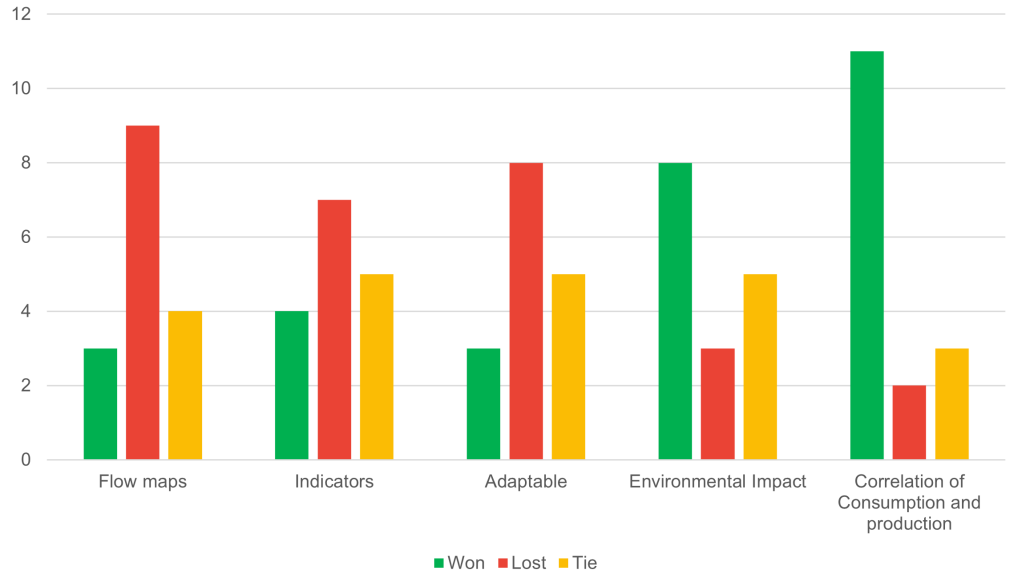

Figure 5.3: Results of the comparison of the criteria proposed

As it can be seen, based on just the amount of times one criterion was more relevant than another, it is possible to claim that the most relevant ones are the correlation of consumption and production, and environmental impact. Numerical results and weighting calculations are shown in Table 5.2.

Besides the inclination towards the correlation aspect, the numbers highlighted in the table show what sub-criteria were more relevant to them. These results revealed an inclination towards an energy flow map for the first criterion, resource losses for the second criterion, which can be done with data already collected for the third criterion, and considers GHG emission for the fourth criterion. In the case of the fifth criterion, although it is the most relevant one, it has no sub-criteria and no other sub-criteria to be compared with.

Based on the criteria proposed, an evaluation of the methods was performed. Then, by using the weights calculated, the methods were ranked according to their total scores. The results of these can be seen in Table 5.3. As indicated by the results, the method that adapts the best to the company priorities is VSM, followed by REC & REF.

It is necessary to clarify that three of the methods reported in Section 5.1 were not included in the evaluation: EMS-CD, MFCA, and MLR. There were three reasons for this decision. First, EMS-CD is a method that is already implemented at the plant. It has been used for several years, involving different departments to track down all

Table 5.2: Criteria collected and weight of their relevance based on answers

Criteria	Global weight	Sub-criteria	Local weights	Global weights
Flow maps	12.89%	Chemicals flow mapping	13.64%	1.76%
		Materials flow mapping	10.00%	1.29%
		Waste flow mapping	22.14%	2.85%
		Water flow mapping	17.77%	2.29%
		Energy flow mapping	**36.44%**	**4.70%**
Indicator	16.95%	Efficiency per resource in %	28.24%	4.79%
		Value added and non-value added consumption	24.02%	4.07%
		Losses	**33.73%**	**5.72%**
		Consumption in Volume	14.01%	2.37%
Adaptable	13.96%	Can be done with data already collected	**63.40%**	**8.85%**
		Can be done with tools and software owned by the company	36.60%	5.11%
Environmental Indicators	24.06%	Considers resource depletion impact categories	43.53%	10.47%
		Considers GHG emissions	**56.47%**	**13.59%**
Correlation of consumption and production	**32.15%**	Considers production aspects that can be linked to resource consumption	**32.15%**	**32.15%**

the possible losses and convert them into costs. Due to this, the contribution of the current project would not be that high if EMS-CD was selected for the assessment. Second, both the EMS-CD method and MFCA are methods in which costs are the main focus. However, based on the meetings that were held with the case company in the project, it was preferred to do an assessment of resources more oriented towards consumption and environmental impact. Third, MLR was a method that, although it was classified as an RE assessment method, it was determined that there were not enough data points in the data set provided by the plant to conduct MLR. This means that the volume of data would have compromised the reliability of the possible results.

Table 5.3: Evaluation of the RE methods selected for the study case

	Methods					
	Criteria	**MFA**	**RVM**	**VSM**	**REC & REF**	**LCA**
Flow maps	Chemical flow map	yes	no	yes	no	yes
	Material flow map	yes	yes	yes	no	yes
	Waste flow map	yes	no	yes	no	yes
	Water flow map	yes	no	yes	no	yes
	Energy flow map	no	no	yes	no	yes
RE Indicators	Efficiency per resource	no	yes	no	yes	no
	Value added and non-value added consumption	no	yes	yes	yes	no
	Losses	yes	yes	yes	yes	no
	Volume of resource consumed	yes	yes	yes	yes	yes
Adaptability	Can be done with collected data	no	no	yes	no	no
	Can be done with tools and software owned by the company	yes	yes	yes	yes	no
Environmental Indicators	Considers resource depletion impact categories	no	no	no	yes	yes
	Considers GHG emissions	yes	no	yes	no	yes
Correlation of Consumption and production	Considers production aspects that can be linked to resource consumption	no	yes	yes	yes	no
Final score (0-1)		0.35	0.55	0.85	0.65	0.39

5.3 Assessment design

5.3.1 Dynamic evolution over time

Based on the findings of data understanding, most consumption generally follows a pattern based on the number of blocks produced, with occasional deviations. These aspects are considered valuable to find underlying reasons for data behavior and resource usage. Therefore the assessment will use monthly data points to include the dynamic behavior of data and RE indicators will be calculated with the same temporal resolution.

5.3.2 RE Method

As mentioned previously in section 5.1.5, value stream mapping is a collection of methods that are adapted based on what is more relevant to show on the assessment. Although in terms of content, each method differs a lot from the other, the overall structure is similar: a value stream map showing relevant indicators for each of the processes. In this context, and due to the relevance of describing not only resource consumption but also production indicators and environmental indicators, the method that was decided to use was G-VSM. As described earlier, G-VSM is characterized by showing the consumption of resources and production of waste and emissions (Marimin et al., 2014). It can be adapted to show consumption at different temporal resolutions (daily, monthly, etc.) and it can be described as a flow map of processes that show different indicators, first at the production level, and then at the process level.

5.3.3 Indicators included in the assessment

It is necessary to clarify that the indicators included in this assessment were adapted for this study case, and they are not the same as the work of (G-VSM). These indicators were collected as reference indicators found in the assessment methods and data available regarding production aspects. With that in mind, indicators were collected at both the cylinder block production level and the process level. Tables 5.4 and 5.5 show these indicators, which are the following:

- **Production Indicators:** At the cylinder block production level, four indicators were identified as relevant to show: Takt time, production hours, range of production hours, and processing time per block (sum of time of simultaneous processes to produce one block). In the case of the production indicators at the process level, cycle time, processing hours, and A.P.Q losses (availability, quality, and performance losses) were selected.
- **Consumption Indicators:** For consumption indicators, at cylinder block production level, all the total consumption per resource for the year 2023 was shown. In the case of process level, processing energy and tools consumption were reported both in total consumed by process, and in percentage concerning

Table 5.4: Cylinder block production level indicators included in the G-VSM. "*" means that the indicator is included if data is available for a given process

Cylinder Block Production	
Production Indicators	**Consumption Indicators**
Takt time (s)	Energy (kWh)
Production hours (h)	Water (m^3)
Range (h)	Quakercool (kg)
Processing time (h/block)	Other chemicals (kg)
	Chips (kg)
	Tools ($R)
RE Indicators	**Environmental Indicators**
Energy (kWh/block)	GWP100
Water (m^3/block)	Acidification
Quakercool (kg/block)	
Other Chemicals (kg/block)	
Chips (kg/block)	

total consumption of all machines. For some particular machines in which data was available, water was also reported.

- **RE Indicators:** The most important RE indicator that was presented was the fraction of resource/block, which is shown for every resource. Inspiration for creating this fraction came from (Dehning et al., 2017), and it allows to show the dynamic evolution of the use of resources for the production of one block. At the process level, the only indicator that could be shown due to the data available was energy efficiency, and it was possible to calculate only in some machines.
- **Environmental Indicators:** As intended from the beginning, the purpose was to select the environmental indicators based on the EU Taxonomy. However, after searching for these indicators in the regulation, and talking to experts inside the company, it was noted that it does not apply to this particular study case. For other types of manufacturing different than the manufacturing of automotive parts, the taxonomy indeed brings specific indicators to compare with. For example, for the manufacturing of aluminum (European Union, 2024a), it is specified in the regulation that GHG emissions are an important indicator, including an upper limit that needs to be met to call the activity sustainable. However, in the case of manufacturing automotive components, the regulation is much more complex.

  Apart from the fact that there is regulation only for contributing to climate change mitigation, in order to call the activity sustainable, it is necessary to

Table 5.5: Process level indicators included in the G-VSM

Process	
Production Indicators	**Consumption Indicators**
Cycle Time (s)	Processing Energy (kWh)
Processing hours (h)	Processing Energy (%)
A.P.Q. Losses (h)	Tools ($R)
A.P.Q. Losses (%)	Tools (%R)
	Water (m^3)*
RE Indicators	
Energy Efficiency (%)*	

meet the "Do not significant harm criteria" (European Union, 2024b). For this, it is necessary to evaluate different criteria such as climate adaptation, water, circular economy, etc. For evaluation, the taxonomy proposes a set of articles with a series of checklists that need to be met. For example, to meet the criteria of pollution prevention, it is necessary to check whether or not a particular set of substances is being used. Another example is water criteria, in which an environmental assessment needs to be carried out to check from where the water is extracted, if water sources are being contaminated by discharged water, etc. Therefore, no indicators were found to be used explicitly without having to make a detailed and extensive evaluation. Because of that, it was decided to use other sets of indicators. For that, it was necessary to analyze the sustainable efforts to understand what are the reasons of the environmental footprint.

After analyzing the efforts of the plant, which were described at the beginning of chapter 4 (4.1.1), it was determined that the main source of environmental impact is the incineration of the remains of quakercool after its usage. In this scenario, and based on the composition of the coolant, which is a mix of petroleum oil, water, and additives (Quaker, 2024), the most relevant environmental impact categories are global warming potential (GWP100) and acidification (Clarens et al., 2008). Therefore, it was decided to select these indicators for the assessment.

5.3.4 Correlation between independent variables

Due to the case company priorities, the assessment will explore the correlation between different variables. This will be achieved by constructing a dashboard of graphs. Correlations will be assessed manually by comparing and analyzing data pairwise of individual variables and collectively in one graph showing the evolution over time. To this end, scatter plots are implemented for pairwise comparison of the calculated RE indicator and the denominator, and a bar chart for collective assessment. Due to the case company's specific interest in energy their energy consumption, a separate analysis is provided with scatter plots comparing energy and production factors.

Calculations of Pearson's correlation coefficient are included to numerically assess the correlation of variables. Pearson's correlation coefficient represents the linear correlation of two independent variables and applies to this case due to the functional dependence of multiple variables in the machining line (Puth et al., 2014). The correlation coefficient has a range of [-1,1] with the absolute value describing the magnitude of linear correlation. The sign expresses if the correlation is negative or positive, meaning if a change in one variable will cause the other to either linearly decrease or increase. A coefficient of 1 or -1 will imply a perfect positive or negative correlation respectively and 0 means that the correlation does not exist.

6

Assessment results

The following chapter will present the assessment result of the study. It includes the following sections: Data set description, Dashboard of graphs, and Green Value Stream mapping. The first section presents the data set for calculating indicators and finding correlations between consumption and production factors. The second section presents the dashboard of graphs used in the assessment to analyze patterns, trends, and correlations between independent variables. This includes the monthly indicator evolution over a year with a monthly temporal resolution, the correlation matrix with all independent with a heatmap, a comparison of indicators and blocks produced, and a comparison of the energy indicator and production factors. The third section presents the results and implementation of Green Value Stream Mapping.

6.1 Data set description

The final data set for calculating indicators and finding the correlation between consumption and production factors includes ten independent variables. Waste or metal chip waste[kg], energy or more specifically electricity[kWh], water[m^3], and Chemicals[kg] split into Quakercool or coolant and other chemicals represent the resource consumption of the machining line. Additionally, it has the number of blocks, which refers to the number of cylinder blocks the case company sells. This variable is defined as the output of the assessment. For production factors, two independent variables are included. These are the processing time and APQ time, aggregated for all machines to get the total hours of the entire machining line for the respective variables. Processing time refers to the working hours of each machine, meaning the number of hours each machine is running the process. APQ is short for Availability, Performance, and Quality and includes losses such as idle time, maintenance time, availability and waiting time aggregated into one variable in hours. Takt time, energy rate of machines, cycle time, and tools are also included in the data set but do not match the temporal resolution.

The data is extracted as different spreadsheets in Excel or directly from the data management system. Data on resource consumption is provided by the case company in spreadsheet format, with each variable in separate spreadsheets. Production factors were manually extracted directly from their system in spreadsheets and pro-

cessed.

6.2 Correlation of consumption and production factors

Various graphs and visualizations are constructed with resource and production data provided by the case company. Analysis and visualizations are presented and explained in the following chapter. All graphs explore indicator correlation and behavior at multiple levels of detail. To exemplify this, conclusions regarding behavior and correlation can be observed on a surface level in the monthly evolution of indicators. The correlation matrix gives a numerical correlation coefficient to confirm the previous conclusion. The scatter plots serve as a means to further investigate the patterns and trends of each indicator and their underlying causes.

6.2.1 Monthly evolution of indicators

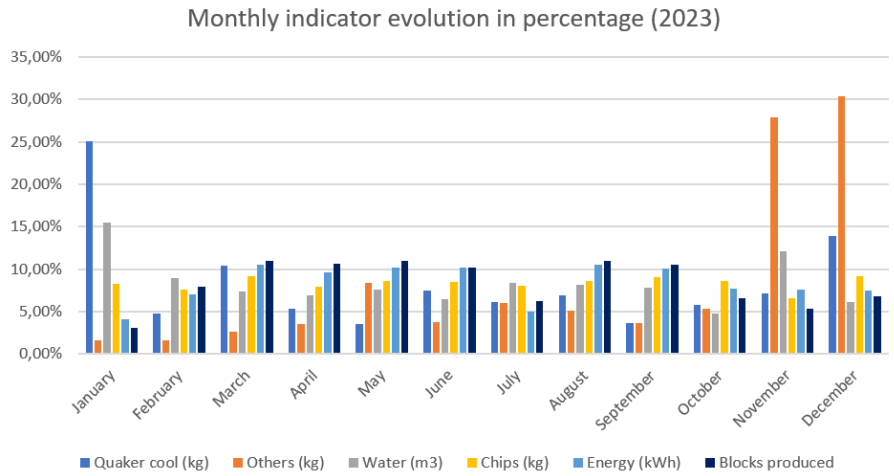

Figure 6.1: Monthly evolution of indicators in percentage based on total value for the respective indicator of resources.

Based on the defined data set, the calculated indicators and quantity of produced blocks are visualized in a bar chart, shown in Figure 6.1. The graph shows interesting behaviors in the data, which implies that something is happening in the machining line. Other chemicals fluctuate between 2% and 8% from January to October but increase significantly to 28% and 30% in November and December. Also, it does not follow the trend of blocks produced which is low in November and December relative to the other months. Quakercool had a higher consumption per block in January and December with 25% and 19% respectively, despite the low number of blocks produced for these months. From November to December, the Quakercool and water indicator values show a disconnect in behavior. Despite the fixed composition of both resources in the cutting fluid, the relation of Quakercool is not clear.

The Hidromation system automatically mixes the necessary water and Quakercool needed to maintain the concentration. The system checks the concentration and if it is below the threshold, it automatically adds more Quakercool until the threshold is met. However, the cause of reduced Quakercool concentration and rate of reduction is not clear. Based on the former facts, it is hard to contextualize the behavior of data with underlying reasons from the system characteristics.

6.2.2 Correlation of independent variables

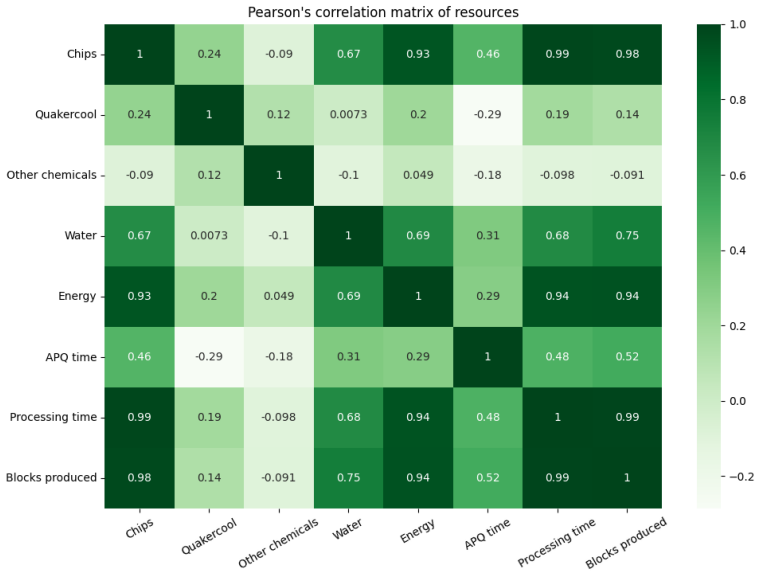

Figure 6.2: Pearson's correlation matrix and heatmap of resources and production factors

The generated matrix and heatmap shown in Figure 6.2 individually compare the correlation of all independent variables in the data set, a darker shade meaning a higher value. A bar representing the scale between the correlation and color is shown on the right sight of the graph. By examining individual correlations, it is possible to identify potential dependencies among multiple variables. Collectively, the variables can affect overall resource consumption meaning that a change in one resource can affect the other. Knowing the correlation enables the investigation of underlying reasons for a reported consumption value.

When observing the matrix row of waste (chips), there are three variables with significant correlation, the first being the number of blocks produced with a value of 0.98. This is expected because the material input to be machined has a set volume with minor deviations due to the tolerances of the cast blocks. The implication is that waste generation is fixed with some differences due to material input. Logically, the correlation should be 1 but this is not possible due to the deviations of cylinder block weight caused by the tolerances. Processing hour and waste have a correlation value of 0.99, 0.01 higher than the number of blocks produced. Waste of metal chips is only generated during machining, which is included in the processing hours. The

observation also explains the correlation with energy due to the machining line mostly consisting of CNC machines. Waste and water have a correlation value of 0.67, indicating a moderate correlation between variables. This demonstrates logical consistency as all machining processes consume water. However, the correlation is relatively low compared to other variables. To reduce the amount of chips, the number of blocks needs to be decreased, resulting in a decrease in energy and water consumption.

The correlation of Quakercool (coolant) consumption is low concerning all independent variables. These results are interesting based on how the manufacturing system operates, specifically regarding the number of blocks produced. The number of blocks to be machined should be a driving factor to the amount of Quakercool, processing time, and energy needed for production and generated metal chip waste. As a result, Quakercool should have a higher correlation coefficient to blocks produced, energy, waste generation, water, and processing time. This indicates possible inconsistencies regarding Quakercool with how the data is recorded. This data is not measured directly, but rather it is an amount that the warehouse of the machining line requests the company to buy. Because of that, it is hard to tell the possibility of over-consumption, since they could buy coolant based on their predictions of the demand. Apart from this, there could be multiple reasons for this to happen.

One possible explanation for this to happen is the degradation of the emulsion, which is the mix of water and coolant. Based on the explanation the company provided, they have to make sure that the concentration of this emulsion is on the right level. If this concentration is too high or too low, there will be changes in consumption (Fuchs, 2024). For example, if the concentration is too high, cutting fluid consumption will increase. If it is too low, there will be a growth of bacteria, reduced life span of tools, etc., which will force the plant to clean the cutting fluid system, evacuating all the remaining fluid, and increasing the purchase use of new coolant.

In this context, one possible hypothesis is that concentration levels are far from the appropriate levels multiple times during a week of production. If the sampling rate on these measurements is not small enough to detect these, they could not be aware of that. This could result in a weekly cleaning at the end of the week due to a fast degradation of emulsion to avoid losses in quality, which results in the replacement of the remaining emulsion, and increasing total emulsion consumption when purchasing. Additionally, there is a possibility that they have a constant sampling rate when the system measures concentration, which could be a problem considering the fluctuation in production.

For example, if in one week of production, the Hidromation system measures concentration levels twice a week, and in the next week, they produce double the amount of blocks, keeping the same sampling rate twice a week could pose a problem. They could lose valuable information when the concentration levels are out of the appropriate range. Because of that, to prevent unnecessary additional cleaning and

increased consumption of coolant, the plant can measure the concentration levels more times during production, especially when they know there will be sudden increases in production to meet demand.

In this way, they could adjust the concentration levels quickly in both low-production and high-production weeks. In case the Hidromation system adjusts the concentration as fast as possible as soon as it is out of range, there could be other possible reasons. Among other possibilities are leakages, incorrect preparation of the emulsion (e.g. water does not present the correct hardness), or possible abnormal high frequency of cleaning. What the company can do in the latter is to check the amount of times cleaning has been done per month, and compare that with Quakercool consumption, along with concentration evolution. This could provide further insights, allowing them to tell if the coolant is degrading faster than expected.

Regarding other correlation values, water consumption shows a high correlation to chips, processing time, and blocks produced. Due to water only being used during processing in the machining line, a high correlation with blocks produced, processing time, and chips is logically coherent. The correlation with energy consumption is moderate and can be connected to the waiting time of machines. When a machine is waiting for a workpiece from the previous process, the machine will be continuously consuming energy but not water

The heatmap shows a high correlation of energy with processing time and blocks produced. Energy is directly affected by processing time which is decided by the number of blocks produced driven by demand. This is apparent due to the correlation coefficient of 0.99 between processing time and blocks produced. However, energy and APQ time have a low coefficient despite e.g. waiting time being the primary energy loss. The main reason for this is the proportion of processing energy compared to the total energy. Since the data is the energy consumed for the entire machining line, a big proportion of energy consumption factors do not correlate with APQ losses. For example, in August, which was the month of highest production, processing energy represented only 40% of the total energy based on estimations. This means that 60% of consumption is allocated to other sub-systems. Examples of these are transportation systems for blocks, ventilation systems, lighting systems, the Hidromation system, etc. This means that the energy consumption of those sub-systems does not correlate with APQ time.

6.2.3 Comparison of RE indicators and blocks produced

Five scatter plots are included that compare the number of blocks produced and resource efficiency indicators, these variables represent the Y-axis and X-axis respectively. All five graphs can be found in Figure 6.3 above. The indicators compared are the metal chip waste, water ratio, other chemicals ratio, Quakercool ratio, and energy ratio in corresponding order. Due to the fixed parameters of the machining line processes the focus should be shifted towards stabilizing resource consumption per block to maintain consistency and decrease variation, specifically, the range

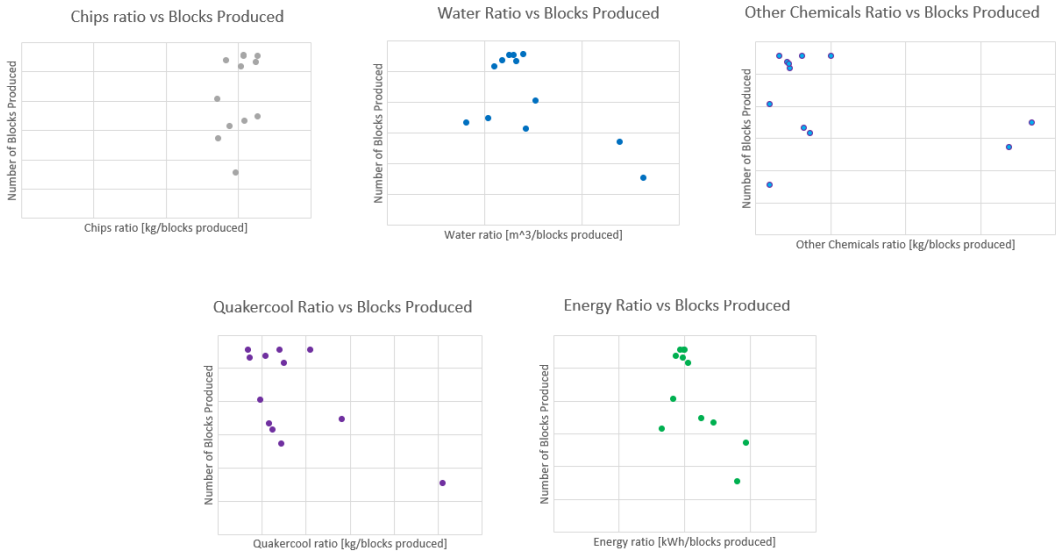

Figure 6.3: Scatter plots of RE indicators for all resources compared to blocks produced.

of consumption per block for similar production volumes, which is the difference between the maximum and the minimum values. Investigating the causes of said variation and potential causes for over-consumption can improve resource efficiency by resolving these issues.

When observing the graph of metal chip waste ratio vs the number of blocks produced, the data points have low indicator variation based on the maximum and minimum values on the x-axis. This is due to the fixed weight needed to be machined from each cylinder block with deviations due to the tolerances of cast cylinder blocks. Since the tolerances do not depend on the machining line, but rather on the supplier, it is logical to have some variation in the amounts of chips produced after removing material from the cylinder blocks.

For the case of water, it was found that this graphic has more variation than the graphic of chips. The total range of the indicator has a maximum indicator value that is higher than the minimum by a factor of 3. Also, the maximum indicator value has half of the production volume of the minimum value. This result can indicate possible over-consumption, which can have multiple explanations. One hypothesis (apart from possible leakages during the waiting of machines) is that the possible uncontrolled frequency of weekly production causes the generation of too much heat.

If machines request water based on the amount of heat generated, when having a high frequency of production, more water will be requested because the inside of the machines does not have time to dissipate the heat, nor do the blocks have time to cool down. This means that, for example, producing 4 blocks in 1 hour could generate more heat than producing the same 4 blocks in 2 hours. In this particular case, it is known that not letting parts produced cool down could have an impact on resource consumption. For example, based on the information given by one employee

from a plant located in the same country where the project was carried out, a high frequency of production resulted in warmer parts, which affected the adherence of paint when painting them. Because of that, more paint was used for warm parts in comparison to cold parts. Based on this, it is possible to see that heat generation could affect some resources, and water could be one of them. To avoid this, it is recommended that the company tries to have a constant rate of production, aiming at the same amount of blocks produced per shift, rather than producing more in one of the shifts.

Regarding the outliers, it was determined that there are two of them: one from November, and the other from January. Apart from possible human errors that could exist, it is difficult to link them to specific reasons. However, what it is known is that both January and November were the months with the highest amount of inactive production days, based on information provided by the company. One possibility is that leakages not only exist when the machining line is active but also when it is inactive. Even if this is not the case, this result could indicate that having inactive the machining line for multiple days could affect resource consumption, which could be valuable if the company finds it relevant.

The comparison of other chemical ratios and the number of blocks produced shows that a majority of data points are confined in a set area. Values in the top right corner of the graph show irregular behavior when comparing the number of blocks produced and indicator values. Despite the number of blocks being stable at the range, the consumption per block increases continuously across 6 data points. Also, two data points show more than three times the consumption of others at a similar number of blocks produced. Although, most data points are within a set limit, the irregular patterns show a high variance of the resource efficiency of other chemicals.

In the case of this resource, it is believed that the variance is mainly due to the purchasing frequency. While going deep into what other chemicals are being used, from a list of 29 chemicals, there are 6 of them that are relevant based on their total weight and can be divided into three categories: lubricant oils, hydraulic oils, and degreasers. For the case of the two hydraulic oils, the data provided by the company says that almost 100% of the consumption is located in 3 different months. Since it is fair to say that this is not possible (since hydraulic oil is required all year round for machines to work), then the most reasonable explanation is that the plant buys huge batches which they store for the rest of the year. In this context, due to the amount of chemicals, and that not all of them they buy in the same months, high variation is logical to happen.

For the scatter plot of the Quakercool ratio, from prior analysis with the correlation matrix, high variation was expected when creating this graphic. This indicates a considerable inconsistency in resource usage of Quakercool per block at similar production volumes. These results can be linked with what was mentioned in the previous chapter. Additionally, since Quakercool and water are mixed in the same emulsion, the reasons for the variance of water could also affect the variance of

Quakercool. For example, the data point with the highest Quakercool ratio, which was classified as an outlier, is from January, the same month that the water ratio was determined as the highest.

For the energy curve, it is possible to see how data points present high variation, with a range of consumption with the maximum indicator value being approximately double the minimum, and multiple data points concentrated around one value at higher production volumes. As can be seen, it does not follow any particular trend. One hypothesis for this behavior is linked to what was already mentioned regarding the processing energy. Since most of the energy is consumed not by machining but rather by a combination of other factors and sub-systems (waiting time losses, transportation of blocks, Hidromation system, lighting system, control system, etc.) the variation possibly comes from those systems. In this case, already mentioned possibilities can affect the variation in some of these sub-systems. For example, the energy usage of the Hidromation system is affected by the amount of water needed, which is affected by the generated heat. Another example is the transportation system, which is also known as the gantry loader. The energy usage of this is affected by the amount of times it has to move the blocks, which depends on the frequency of production, leading to different waiting times. Based on that, for energy, it would be needed to measure the power rate of more sub-systems along with their active time, and it is the only way to be able to point to specific reasons. Overall, it appears to be the most complex variable that depends on several other variables (including other resources), which makes it difficult to describe and look for trends and patterns. Therefore, the company could take into consideration the fact that the proportion of non-machining energy is higher at every production volume, which could be valuable for them to look at first.

6.2.4 Comparison of energy indicator and production factors

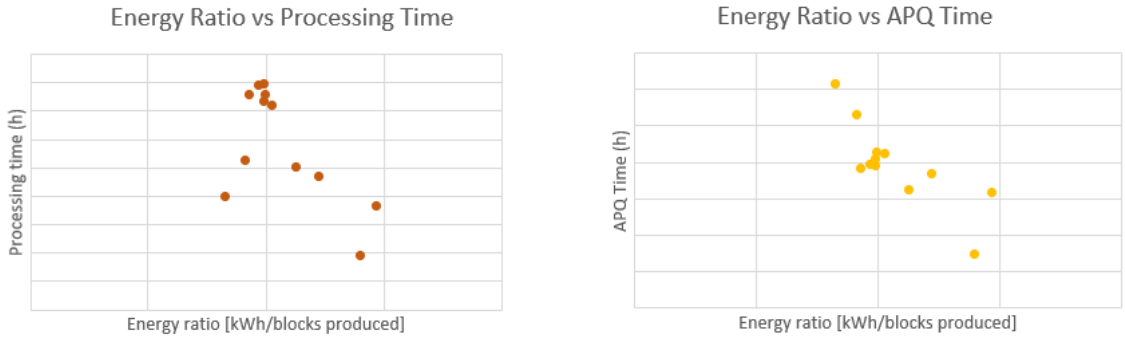

Figure 6.4: Scatter plots of energy indicator compared to production factors.

Two independent production variables that can be compared to energy are processing and APQ time. APQ time refers to the waiting time of machines that can be translated into losses in terms of energy consumption. Scatter plots for this compar-

ison are shown in Figure 6.4 above. The left scatter plots compare the processing time and energy ratio, while the right one compares the APQ time with the energy ratio. Regarding the first one, since processing time showed a very high correlation with blocks produced, the shape of this graphic is similar to the previous graphic of energy ratio against block produced (6.3). However, regarding the graphic on the right, it is possible to visualize what appears to be a negative linear correlation where an increase in APQ time decreases the energy ratio. In other words, the more losses, the less energy consumed per block. One hypothesis for this to happen is that during APQ time, machines waiting and the other sub-systems aside from machines are consuming a lot of energy in a more controlled way, which shows the importance of measuring the energy of different sub-systems while the machines are not operating, along with machines itself. In this sense, it is not expected from the left graphic to present a linear correlation because the other subsystems could present high variation in consumption when being active.

This does not necessarily mean that the best strategy for the company is to reduce the lost time as much as possible but rather to try to keep production close to its maximum. Lost time can be reduced by simply producing less, but since the company is aiming towards 24 hours of production, the losses in energy are quite high if they cannot produce the same amount of blocks daily. If they need to adjust the demand and produce less, it could be reasonable to think about fewer hours of production per day on some days, but with the same aim of producing at a high frequency. In this context, it is worth noticing that, keeping a high frequency of production could affect water consumption, as it was already explained due to the heat generation. However, since they have a closed-loop water system, the water losses of having a high water ratio are probably not as important as the energy losses when they have a high energy ratio. This behavior is only a hypothesis since trying to achieve a constant high production volume could present other problems in the company and could not be feasible based on the varying demands of customers. Overall, based on data behavior, higher production volumes result in more stable energy ratios.

Additionally, these findings reveal that the higher the production, the more controlled the energy ratio. As it can be seen, this results in the behavior of the energy ratio clustering at a certain value as seen in the highest points in the graph. In total there is 6 data points with this behavior, which is half of the year of production. This can be reflected in the graph to the right, in which for those six data points (the ones that are clustered), the APQ time value is also relatively fixed, showing a relatively stable energy ratio. This could be defined as the optimal number of lost hours required to maintain a low dispersion of energy ratio during high production. However, APQ losses are a consequence of how the production works, and not the other way around. In other words, it is easy for the company to aim to produce a particular number of blocks, rather than aim for a specific number of hours of APQ losses. This corroborates the benefits of producing at high frequency. Besides, with the data already collected, it can be stated that for this high production volume of

the six data points, the range of the energy ratio is relatively low.

6.3 Green value stream mapping

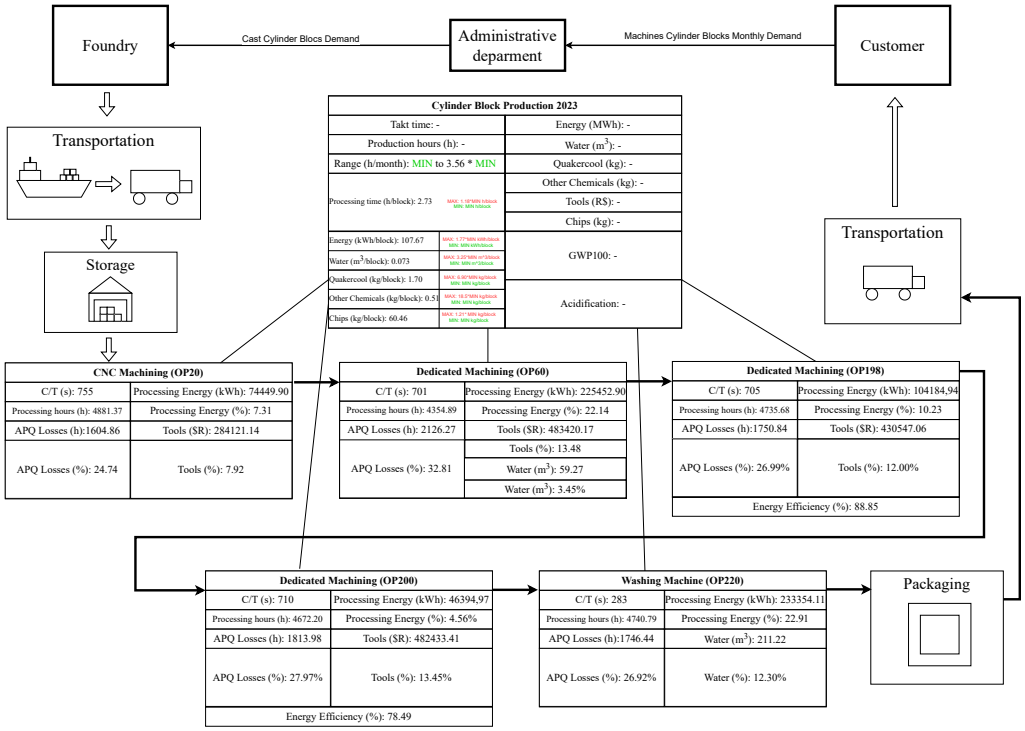

Figure 6.5: Green Value Stream mapping for most relevant processes in machining line

The overall structure of the current G-VSM presented in Figure 6.5 follows the structure presented in the work of Marimin et al., 2014. Based on that, other steps in production different than machining, such as casting, transportation, storage, and packaging, are shown in the assessment. As the core of the assessment, all indicators described in the assessment design section are included. They represent important characteristics at both the cylinder production level and machine level. Due to the large number of processes running in the machining line, it was determined that only the most critical processes are displayed separately in the assessment. However, other processes can be added if needed. These were selected based on the following reasons:

- **CNC Machining (OP20):** It is the process with the highest processing time of all.
- **Dedicated Machining (OP60):** It is the process with the highest tool change cost. Apart from that, it was stated by the company that the machine is a special drilling process that requires specific characteristics (pressure, chip removal rate, etc.). Due to this reason, it is separated from other machines in the G-VSM.

- **Dedicated Machining (OP198):** It is the process that represents the bottleneck of the machining line.
- **Dedicated Machining (OP200):** OP200 is the process with the highest losses in equipment failure and cutting tools according to their assessment.
- **Washing Machine (OP220):** Based on estimations, it is the machine that consumes the highest amount of processing energy.

As can be seen in the result, only for machines OP60 and OP220, water usage was calculated due to data availability. It was a similar case with the indicator of energy efficiency, which was calculated only for machines OP198 and OP200. In that case, approximations were made. By using the processing time data, and the rate of power that each machine consumes per hour (kWh/h) the usage of processing energy was found by multiplying these values. Then, this result was divided by the real value that was measured. As a result, a fraction of efficiency was found. Overall, both OP198 and OP200 have high efficiency, but if the company wants to increase efficiency in one of these machines, it is better to focus on OP198. While it is true that its efficiency is higher (88.85%), its power rate is more than double the power rate of the other machine, consuming more than double for every hour of processing. Overall, if they would like to find the energy efficiency of the most relevant machines, they need to focus on machines OP60 and OP220, since the two combined consume around 45% of all machines consumption. It is possible to see this in the Processing Energy indicator in the G-VSM of both machines.

Regarding the values of the indicators found, at the cylinder block production level, it is possible to see the results of the average resources per block produced, along with their maximum and minimum values to see the dispersion of data. Other chemicals were found to be the flow with the highest range since the maximum is around 18 times more than the minimum. Then, it is followed by Quakercool and then water. Besides this, the flow with the lowest range was metal chip waste, with the maximum being around 1.2 times the minimum value. It is worth noticing that the range was not included in the original G-VSM found in the literature, adding extra value to the indicator found, and including what was found in the previous graphics.

Apart from the energy consumption of OP60, other indicators can show how critical it is. It is the machine with the highest losses in terms of time according to APQ Losses, and the highest consumption in tools. According to the company, in terms of the APQ, waiting is the main reason for this high value, followed by undefined/not reported problems, and equipment errors. In terms of tools, this result is not coherent with their analysis in which machine OP200 was the machine that consumed the most amount of tools, as previously mentioned. This difference could show some problems with the calculations or data collection, which means that it would need to be checked by the company if they think it is valuable to focus their efforts on reducing tool consumption.

In addition to these indicators, for every indicator that presents a range, the months in which they reached their highest and lowest values were identified. Due to the extensiveness of this information, it was written in Table 6.1. Although it is not possible to see a clear trend regarding the consumption indicators in terms of the highest and lowest values, it is not the same for the RE indicators. In the latter's case, every indicator's highest value is in either November, December, or January. This means that per block produced, the consumption of all main resources increases at the beginning and end of the year. What makes these months special is that these months are the ones that present the highest amount of inactive days, which could be something relevant for the company to check. As was previously mentioned, there could be leakages or unexpected resource consumption, which is the main hypothesis. Either way, since these inactive days could be unavoidable (since some of them are holidays) what they can do to know more about it if they want to explore this possibility is create strategies to monitor more aspects of the behavior of operators. This means gathering more information on what the operators do 1 week before going into a break, and 1 week after returning from the break. When doing this, and comparing that with the resource consumption of the same weeks, possible patterns and trends could appear.

For example, according to the company, in 2023 they usually used their Sundays to do maintenance. However, in December, the last day of activities was a Wednesday, with a full day of production. This could mean that in their last week of production, which was shorter, maintenance could not have been done, which could cause problems when starting their operations again. This is one possible finding that can appear if they use the strategy of monitoring weeks after and before breaks, and comparing them with normal weeks of production.

Table 6.1: Months with the highest and lowest values of the cylinder production level indicators

Consumption Indicators				
	Month of least consumption	Value (from total)	Month of highest consumption	Value
Energy (kWh)	January	4.10%	August	10.58%
Water (m^3)	December	5.27%	August	11.34%
Quakercool (kg)	February, May, July, September, October, November	5.26%	March	15.79%
Other Chemicals (kg)	January	0.67%	December	28.07%
Chips (kg)	January	2.95%	March	11.76%
RE Indicators				
	Month of least consumption	Value (from average)	Month of highest consumption	Value
Processing time (h/block)	November	-14.37%	December	+7.02%
Energy (kWh/block)	July	-22.72%	November	+36.90%
Water (m^3/block)	October	-42.96%	January	+85.39%
Quakercool (kg/block)	May	-57.95%	January	+204.40%
Other Chemicals (kg/block)	February	-80.52%	December	+277.95%
Chips (kg/block)	November	-20.90%	December	+9.55%

7

Discussion

7.1 Relevant findings

During every stage of the project, it was common to find limitations and difficulties of all kinds. These caused to redefined multiple times the direction of the assessment selection, design, and execution, leaving behind the existence of facts, possibilities, and uncertainties that the company needs to consider to either explore further or disregard for projects that come after. Based on this, these were the most relevant findings:

- **Searching about RE:** Although this project compiles a list of possible methods that can be used for assessing resource efficiency, searching through the databases has shown that there are numerous additional methods. This means that, although multiple methods can be classified as RE methods, they can not be found using the main keyword of resource efficiency. Additional keywords such as sustainable performance, environmental productivity, resource consumption, and resource analysis, among others, need to be counted if there is a desire to explore more methods. Based on the research, it was determined that the Journal of Cleaner Production (Elsevier, 2024) is the most relevant one for this topic.
- **Relevance of EU Taxonomy:** Although EU taxonomy was explored at the beginning of the project, after reviewing the regulation that applied to the study case, and talking to experts from the company regarding the use of it in RE assessment, it was decided not to consider EU taxonomy. The main reason is that, for some specific types of production systems, like the automotive manufacturing ones, indicators regarding environmental impact were not explicit. This means that classifying an activity as sustainable using this policy was not about checking specific indicators not to be higher than an established upper limit (e.g. water usage), but rather a detailed assessment that required meeting multiple lists of criteria that check other aspects such as location of the plant, usage of allowed chemicals, purpose of the production of the parts, etc.
- **Additional data:** The plant showed that they were recording resource data since 2020. However, data from the previous years was not considered due

to two reasons: completeness and changes that occurred in the company. Apart from the fact that not all resources were recorded since 2020, neither in the same temporal resolution, the plant consistently experienced significant changes every year from 2020 until 2022. First, 2020 was the year of the pandemic, meaning it was the lowest production of all this for years due to reasons unrelated to production. Second, in 2021 and 2022 they executed a major project regarding the enhancement of the machines, which they finished by the end of 2022. Due to this, these years can be seen as years in which the production was going through constant changes. As a result, it was decided that the most complete and stable year was 2023, the year in which the analysis was assessed.

- **Additional machine level data:** Despite the possibility of identifying potential inefficiencies based on data behavior, it can be more concrete and specific. With machine-level data, the assessment results can link inefficiencies or issues to individual machines. Data with this level of detail was not collected and these aspects of the assessment could not be further explored. However, some data are collected per machine but are aggregated for different groupings or sub-systems. In other words, the data is accessible by the case company but is not saved in spreadsheets or information systems.
- **Data Gaps:** Although it is true that lack of data was an issue in this project, in reality, there were only gaps found in one file. In this file, measurements were missing for some months for some machines. For this, the only way to get that value is through additional measurements, since other ways of filling data gaps were found not feasible to work. Strategies like interpolation, predictive models, or fitting data to a function, would require more data per month from other years. Apart from that, the strategy of estimating these values would require measurements of the power consumption of active machines during not-processing events (e.g. waiting, maintenance, etc.), and that data is not been measured. The only gap that was filled was the active power rate of one particular machine (OP198). This was possible to calculate through estimations based on their production data per machine (processing time and APQ time) because that machine is one of the few in which they have measurements of energy consumed per month.
- **Additional production indicators:** Several production variables were not included in the assessment, although they were listed for possible exploration from the beginning of the project. Variables such as tool utilization rates, workpiece hardness, tolerances, idle power, and equipment errors, were found to be relevant since they could be linked to resource consumption. Nevertheless, the time constraints of the project and the difficulty of its collection for some of them (caused by the time required to retrieve it from their monitoring system) were the main reasons not to include them.
- **Meaning of the results:** Without accounting for the source of errors and

credibility of results, discussed in Section 7.2, there could be multiple reasons for the high variability found on resource inputs. Possible leakages, frequency of production, frequency of purchase, coolant degradation, excessive cleaning, etc., were the ones proposed to explain the results. In the case of leakages, that is something that the plant claimed is already happening for one of the resources. Additionally, from exploring different files and documentation in their database, it was found that they are also aware of the overestimation of coolant. Although further exploration will be needed to link these findings with their calculations if the company desires to, some ways to prevent over-consumption were given.

- **G-VSM and EMS-CD:** After executing the assessment, it was decided to explore how the results could be linked with the RE method the plant has already implemented in the past, which is the EMS-CD. According to their assessment, the two biggest losses were the use of cutting tools and equipment failure. By analyzing the reasons behind equipment failure in detail, it was found that the most relevant variable for the highest cause of failure was breakdown time. This finding was particularly interesting since, as it can be seen in the G-VSM performed, the difference between the maximum and minimum processing time indicator values is quite low. What it means is that, if the processing time has a relatively low variation, machining settings are similar every month, and all resource inputs have higher dispersion, there could be unexpected but highly relevant resource losses while machines are not processing. This was something that was desired to be explored by the inclusion of the APQ losses in the assessment, but it was not possible to corroborate this finding for total consumption because of the low correlation of all resources and APQ according to the heatmap(6.2). However, APQ is still a relevant finding based on the behavior found in Figure 6.4. This means that they could use other data from their own assessment that they know it was measured during APQ losses, finding more correlations.
- **Contribution to research and practice:** The main contribution to the research and practice of this project is the list of methods found in the literature and the assessment selection method. If desired by other sections of the company, these could be used to analyze what assessment is suitable at another facility. Other findings, such as data quality and indicators proposed, although they are relevant for the current project, are subject to the data already collected in the company. Therefore, by having better data quality, more indicators can be proposed, increasing the value of the assessment.

7.2 Source of errors and credibility

There are some aspects that can potentially cause errors and affect the credibility of results. The data characteristics are essential due to the data being utilized to calculate and find the correlation of RE indicators, consumption, and production

factors. Some aspects of how data is collected or estimated can be a potential source of error.

Energy is not a measurement collected directly from the machines but is an estimation. The system that collects energy data aggregates multiple substations or production areas. This means that the machining line energy consumption is calculated based on the total and an estimation that the area consumes a certain percentage of that. The chemical data values are not the exact consumption of the machining line but are the values of what is requested by the company. The number of tools used could not be calculated while the cost of tools is approximated. Cost is not an accurate measure of the number of tools either as the world economy has changed significantly during the years in which data was provided. The number of blocks produced used in calculations was the units that were sold and not the actual quantity that the machining line produced. However, despite the difference being low, this is still a potential cause of error that can affect the reliability of the results.

The number of data points is few, reducing the significance of the results regarding the correlation of independent variables. Only data from 2023 could be included as other years had missing data regarding resource consumption. As a result, only 12 data points could be included in the assessment in a small time frame of one year. This was a problematic aspect due to the continuous improvement project in the company. This meant that the performance and consumption of resources changed every year, meaning that comparing data across those years would be misleading. Therefore, more data is needed over a longer time frame with similar production conditions to improve the overall results and significance. Despite a lower significance due to data characteristics, the means used to find correlations can be beneficial for identifying patterns and deviating behavior to reveal underlying reasons causing variance in resource utilization and efficiency.

Data required to calculate the environmental impact of Quakercool could not be collected. This data is not handled by the company's powertrain production but by another function within the company. Due to time constraints, the information could not be accessed before the deadline. As a result, the Green Productivity Index indicator used in G-VSM could not be calculated, due to requiring the environmental impact. Consequently, this reduces the overall value and benefit of the assessment.

To collect data on the prioritization of criteria, only a survey was utilized. Only the quantitative data collection methods were used to this end which can reduce the validity of the weighting of criteria. It is beneficial to combine qualitative and quantitative data collection methods to cross-examine the findings of the methods to check the validity of results (Densombe, 2014). Also, data gathered from qualitative collection methods provide a more detailed understanding compared to a standalone survey. The survey included employees and experts directly involved in the project but consisted of only four respondents. The low number of respondents can reduce the statistical significance and credibility of criteria weights if the participants' answers are not perfectly aligned with the company's priorities.

All decisions made during the project are based on theoretical knowledge researched in literature, knowledge provided by industrial experts, and company priorities and objectives to ensure strategic organizational alignment of results. As a result, different perspectives are integrated and considered, thereby reducing biases from said sources. In other words, the project and its methodology were executed and designed objectively and triangulation was achieved. The overall methodology and results produced in those regards are credible despite potential sources of errors.

7.3 Automation of data handling

In this project, data handling refers to all steps involved in which data was utilized to achieve the goal of conducting the assessment. In total, there were four steps involved: collection of data, storage of data, exploration of data, and calculations. Based on this, it is possible, if necessary, to automate all stages involved. Regarding the automation of the last steps, this is further discussed in Section 7.4. In the current section, the automation of the first two steps is discussed.

Data was collected in different ways for this particular project, and it was done according to Table 7.1. As it can be seen, most data is collected manually, and most of the files were created for other purposes inside the company. Because of that, it is possible to say that there is room for improvement regarding automation. Overall, every resource can be collected automatically with the use of additional equipment. To do that, an approach similar to building a monitoring system can be used (González et al., 2022). With this approach, new sensors should be installed and connected to a controller that powers and controls sensor behavior (e.g. collection rate). Additionally to this controller, there should be an edge computing device that allows to send the data through the network of the company to where it will be stored. The reason for this is that each resource is being measured at a different place in the plant, making it difficult to use wires for transmission.

Resources	Method of collection	Purpose of creation
Energy	Manually and automatically	Arranged for the project
Water	Manually	Other finalities inside the company
Tools	Manually	Arranged for the project
Coolant	Manually and automatically	Other finalities inside the company
Other Chemicals	Manually and automatically	Other finalities inside the company
Metal Chips	Manually	Other finalities inside the company
Production data	Automatically	Other finalities inside the company

Table 7.1: Summary of how data was collected for this project

One example of the type of equipment that can be used for both the controller and the edge computing device is a single-board computer, such as a Raspberry Pi (Raspberry Pi, 2024). In this particular scenario, it would be necessary to install more than one controller since every resource is being measured far away from each

other in different locations, which will require individual power sources. Then, the data collected would be sent to a database through the network. This will require the use of either the databases of current information systems (such as the ones that are used for energy and production data) or the creation of a new one.

Based on the above, it could be possible to automate the collection of each one of the resources, installing new sensors capable of being connected to a controller that would send data when required. While it is possible to make this, it is difficult to get a clear picture of the benefits this will bring the company. One of the main reasons is the cost. The company would have to invest in equipment, training, and maintenance of new devices. Not only that, but this solution would only work for conducting the current assessment, probably gathering a few data points per resource each month. If other assessment, such as an LCA, wants to be made by using automation, additional equipment will need to be installed to measure the inputs and outputs of each process. Even in that scenario, the main reason for automating should be the repetition of the assessment, and that is subject to the company's goals. If a particular assessment is not fulfilling requirements, it will be changed, which will be reflected in the automated solution.

Because there are no clear benefits regarding automating the first step of data handling, which was data collection, it was determined that the step that will be more beneficial for the current manufacturing system in terms of automation is the second step, which is storage. Data storage is currently decentralized and resource data are located and accessed through different systems. Having data stored and accessible in one information system or database would alleviate manual and automated data handling. This does not only reduce time but also confusion by eliminating the need to navigate multiple information systems. Therefore, the company can aim to centralize the data in a database, in an existing or new information system.

Based on the current technical conditions of the manufacturing system, there is a suggestion for implementation that balances the trade-off of cost and benefit. The company's current data collection practices require a major effort to locate and arrange data into one dataset for the assessment, especially since the data is stored in spreadsheets of different formats. Due to that, it would be beneficial to implement an extra and simple protocol that would automate data storage. One additional column could be added to each file, making employees fill it during their daily tasks whenever they add data. This column will be filled based on whether data from the file is needed for the assessment. Once filled, this data will be automatically imported to another file, which can be done online with a spreadsheet editor such as Excel. The reason to add an extra column is that the file format could change over time based on the tasks employees need to perform with each file. Therefore, to ensure that data will be there for the assessment even if the file changes, an additional column in which they write data is suitable. In general, considering the company has already implemented an assessment (EMS-CD), it is necessary to create the goals of a new assessment based on what the current assessment can not do for them. Then, with the goals understood and the benefits written, automation can

be taken into consideration if repetition of the assessment with the high frequency of data collection is a requirement.

7.4 Future work

This assessment was performed by handling data manually. Data was provided in spreadsheets which were manually moved, integrated, and visualized. For future work, the development of a software solution is recommended to automate the assessment. This enables the company to significantly reduce the time to perform the assessment. This idea was explored in the project, but could not be finalized due to time constraints. This includes importing necessary data, calculations of indicators, generation of the dashboard of graphs, and exporting results in a document format such as PDF. As a result, these results can be integrated with the existing digital platforms of the company. An issue that needs to be addressed and improved is how data is imported. Ideally, data should be extracted directly from the database through an API. Specifically, the possibility to access all production factors through the API of their manufacturing monitoring system. This enables the extraction of needed data without constraints due to structure. This requires a good infrastructure, where data collected needs to be available and accessible in a database through IT solutions. If this infrastructure is lacking, importing data from spreadsheets is another option. The format of data spreadsheets needs to be considered in this case. Current formats have unique structures and additional contents making it difficult to generalize the code. Multiple exceptions and conditions are needed for extracting relevant data from the spreadsheets. Therefore, the required data for the assessment can be integrated into one spreadsheet, reducing the number of files to be handled. If the spreadsheets are to be provided separately, the structure should be identical to alleviate the implementation of code. As a result, a single software solution can be applied to multiple scenarios, thereby increasing its value.

In the early stages of the project, benchmarking was initially included as a planned activity. This could not be done due to the time constraints of the study, but it is recommended for future work to compare the results produced. Similar methods and indicators should be applied for a manufacturing system producing similar components. An interesting aspect would be to compare the variance of calculated indicators to find similarities or discrepancies and their underlying reasons. The project conducted a single-case study, meaning that benchmarking is necessary to validate its results and methodology.

8

Conclusion

The project implemented a single case study evaluating the resource efficiency of a manufacturing system, more specifically a machining line as the pilot area. This was done by leveraging existing data to calculate indicators and identify potential issues and their underlying causes through data correlation. Three research questions were investigated for this purpose and the results aimed to answer these.

The first research question was partially answered in the study. An AHP approach for evaluation and selection of methods was utilized. A survey was employed to collect data from involved employees and experts within the case company regarding their priorities of benefits from an RE assessment. However, issues regarding the volume of answers affect the overall value and reliability of the evaluation and selection method.

The second research question was fully answered with the results produced. Various indicators were calculated that could indicate inefficiencies in production by analyzing the variance of resource consumption. Correlations of resource consumption and production factors were observed to identify trends and behavior that make it possible to identify potential issues regarding resource consumption to be resolved.

With the results from the study, the third research question could not be answered. Assessment results can indicate issues regarding resource consumption in production and can potentially bring benefits if resolved. However, the results do not reveal specific causes and concrete improvement plans could not be suggested. Therefore, the possible benefits of the assessment for a manufacturing company cannot be validated.

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A

Survey questions

A.1 Questions comparing criteria

Please select the category that represents you the most

- [ ] Employee at Company 1
- [ ] Employee at Company 2
- [ ] Researcher
- [ ] Operations employee not working at neither case company

What is your role in your current position?

Q1. Flow maps vs Indicators: Which is more important to you?*

- [ ] Flow maps
- [ ] Indicators
- [ ] None of them is more important than the other one

Q2. Flow maps vs Adaptable: Which is more important to you?

- [ ] Flow maps
- [ ] Adaptable
- [ ] None of them is more important than the other one

Q3. Flow maps vs Environmental Impact: Which is more important to you?*

- [ ] Flow maps
- [ ] Environmental Impact
- [ ] None of them is more important than the other one

Q4. Flow maps vs Correlation of Consumption and Production: Which is more important to you?*

- [ ] Flow maps:
- [ ] Correlation of consumption and production
- [ ] None of them is more important than the other one

Q5. Indicators vs Adaptable: Which is more important to you?*

- [ ] Indicators
- [ ] Adaptable
- [ ] None of them is more important than the other one

Q6. Indicators vs Environmental Impact: Which is more important to you?*

- [ ] Indicators
- [ ] Environmental impact
- [ ] None of them is more important than the other one

Q7. Indicators vs Correlation of Consumption and Production: Which is more important to you?*

- [ ] Indicators
- [ ] Correlation of consumption and production
- [ ] None of them is more important than the other one

Q8. Adaptable vs Environmental Impact: Which is more important to you?*

- [ ] Adaptable
- [ ] Environmental impact
- [ ] None of them is more important than the other one

Q9. Adaptable vs Correlation of Consumption and Production: Which is more important to you?*

- [ ] Adaptable
- [ ] Correlation of consumption and production
- [ ] None of them is more important than the other one

Q10. Environmental Impact vs Correlation of Consumption and Production: Which is more important to you?*

- [ ] Environmental impact
- [ ] Correlation of consumption and production
- [ ] None of them is more important than the other one

A.2 Questions comparing sub-criteria

Q11. Chemical flows mapping vs Materials flow mapping: Which is more important to you?*

- [ ] Chemical flows mapping (lubricant and coolants)
- [ ] Materials flow mapping (raw material, cutting tools and consumables)
- [ ] None of them is more important than the other one

Q11. Chemical flows mapping vs Waste flow mapping: Which is more important to you?*

- [ ] Chemical flows mapping (lubricant and coolants)
- [ ] Waste flow mapping
- [ ] None of them is more important than the other one

Q12. Chemical flows mapping vs Water flow mapping: Which is more important to you?*

- [ ] Chemical flows mapping (lubricant and coolants)
- [ ] Water flow mapping
- [ ] None of them is more important than the other one

Q13. Chemical flows mapping vs Energy flow mapping: Which is more important to you?*

- [ ] Chemical flows mapping (lubricant and coolants)
- [ ] Energy flow mapping
- [ ] None of them is more important than the other one

Q14. Material flow mapping vs Waste flow mapping: Which is more important to you?*

- [ ] Materials flow mapping (raw material, cutting tools and consumables)
- [ ] Waste flow mapping
- [ ] None of them is more important than the other one

Q15. Materials flow mapping vs Water flow mapping: Which is more important to you?*

- [ ] Materials flow mapping (raw material, cutting tools and consumables)
- [ ] Water flow mapping
- [ ] None of them is more important than the other one

Q16. Materials flow mapping vs Energy flow mapping: Which is more important to you?*

- [ ] Materials flow mapping (raw material, cutting tools and consumables)
- [ ] Energy flow mapping
- [ ] None of them is more important than the other one

Q17. Waste flow mapping vs Water flow mapping: Which is more important to you?*

- [ ] Waste flow mapping
- [ ] Water flow mapping
- [ ] None of them is more important than the other one

Q18. Waste flow mapping vs Energy flow mapping: Which is more important to you?*

- [ ] Waste flow mapping
- [ ] Energy flow mapping
- [ ] None of them is more important than the other one

Q19. Water flow mapping vs Energy flow mapping: Which is more important to you?*

- [ ] Water flow mapping
- [ ] Energy flow mapping
- [ ] None of them is more important than the other one

Q20. Efficiency per resource (output/input) vs Value-added (VA) and non value-added consumption (NVA): Which is more important to you?*

- [ ] Efficiency per resource per process (output/input)
- [ ] Value-added and non value-added consumption (efficiency per resource per VA or NVA activity)
- [ ] None of them is more important than the other one

Q21. Efficiency per resource (output/input) vs Resource losses: Which is more important to you?*

- [ ] Efficiency per resource (output/input)
- [ ] Resource losses
- [ ] None of them is more important than the other one

Q22. Efficiency per resource (output/input) vs Visualization of consumption based on only volume: Which is more important to you?*

- [ ] Efficiency per resource (output/input)
- [ ] Visualization of consumption based on only volume
- [ ] None of them is more important than the other one

Q23. Value-added (VA) and non value-added consumption (NVA) vs Resource Losses: Which is more important to you?*

- [ ] Value-added and non value-added consumption (efficiency per resource per VA or NVA activity)
- [ ] Resource Losses
- [ ] None of them is more important than the other one

Q24. Value-added (VA) and non value-added (NVA) consumption vs Visualization of consumption based on only volume: Which is more important to you?*

- [ ] Value-added and non value-added consumption (efficiency per resource per VA or NVA activity)
- [ ] Visualization of consumption based on only volume
- [ ] None of them is more important than the other one

Q25. Resource Losses vs Visualization of consumption based on only volume: Which is more important to you?*

- [ ] Resource Losses
- [ ] Visualization of consumption based on only volume
- [ ] None of them is more important than the other one

Q26. Data Availability vs Current Inside knowledge: Which is more important to you?*

- [ ] Data availability (assessment can be done with available data)
- [ ] Current Inside knowledge (assessment can be done with tools and knowledge already owned by the company)
- [ ] None of them is more important than the other one

Q27. Resource depletion impact categories vs Greenhouse Gas Emissions: Which is more important to you?*

- [ ] Resource depletion impact categories (ways in which depletion of resources in the machining process can affect the environment)
- [ ] Greenhouse Gas Emissions (GHG emissions)
- [ ] None of them is more important than the other one

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