A Product Configurator Framework for Integrating the Embodied Product Carbon Footprint

- With a dedicated focus on automated assembly processes at AAU Smart Production -

Master Thesis

Manufacturing Technology

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Abstract:

As the demand for electricity consumption is increasing yearly, understanding and characterizing indirect CO2 emissions associated with the energy consumption in manufacturing has become prevalent. The aim of the study is to employ technology means and develop a proof-of-concept to (1) monitor and quantify the electrical energy used for the assembly processes, (2) calculate and aggregate the electrical energy emission data (kgCO2e/kWh) for the assembly processes, (3) ascertain the embodied emission data for the assembled product variants and (4) create a product configurator, which shows an estimation of the embodied emission data for various product variants. The study is to be carried out on the FESTO assembly line, part of AAU production lab facility.

Preface

It would have not been able for the hereby presented project to be completed without the help of our attentively involved supervisor Chen Li and collaborator Casper Schou whom eagerly shared their knowledge, resources and experience to facilitate the formulation of the project. A special gratitude goes for the uninterrupted feedback on the work conducted and scope formulation necessary for attaining the study theme and requirements.

The analysis is solely conducted at AAU smart production line, on the FESTO cyber-physical factory, qualified for the Industry 4.0 paradigm.

The presented project was conducted as part of the Manufacturing Technology Master Thesis at Institut for Materialer og Produktion, Aalborg University - The Faculty of Engineering and Science.

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Chapter 1

Introduction

As the demand of energy has intensified along with the digitization, the industrial sector (currently accounting for 25.35% [1] of the total European energy consumption, ranks second place in the most energy consuming economy sectors, faces responsibility to reduce energy consumption and increase efficiency. The manufacturing sector energy consumption powers machinery, compressors as well as ventilation, heating and air conditioning, to mention the most common equipment.

In a typical manufacturing setting, the operation efficiency and planning of the manufacturing activities involve criteria related to economic metrics such as material costs, labour costs and capacity adjusted to market demands. Thus, the decisions related to energy consumption have not been considered a priority when establishing a manufacturing strategy [2].

Nevertheless, as the global trends in consumer behaviour become more sustainable-oriented, [3], the taxation on carbon emissions continues to rise and the sustainable manufacturing paradigm gains more and more attention. In this new context, providing environmental information data becomes a competitive-advantage strategy in an increasingly environmentally-conscious marketplace [4].

With the technological development and communication technologies, the information about products and their production can be compiled into ICT systems, such as configuration systems, which connect the consumer to the production capabilities.

Thus, the product structure carrying specific information, enables consumers to have an impact on the product configuration, enabling an active choice over the components, order acquisition, procurement, operations, etc. [5].

As the AAU manufacturing context is based on an Assemble-To-Order (ATO) strategy, it permits the use of product configurators to bind the business processes with product related data in various order processing stages, from the *specification process* and *order inquiry* to *order completion* during which the configured product is sent to production.

1.1 Product Environmental Information

Providing environmental information is a competitive advantage strategy which companies can make use of to differentiate from competition, in an increasingly environmentally-conscious marketplace [4].

When assessing environmental performance of a product, the stages that a product undergoes are identified and assessed, spanning from "$cradle - to - gate$" (material extraction and pre-processing), "$gate - to - gate$" (a delimited stage) to "$cradle - to - grave$" (from material extraction all the way to end-of-life), as seen in Figure **??**.

At first sight, the accountability of GHG emissions for a product might seem like a trivial task. Nevertheless, there are many steps involved in product-life-cycle GHG accounting, as the product goes through stages of *pre-processing*(raw-materials), *production*, *distribution and storage*, *production*, *use* and eventually *end-of-life*.

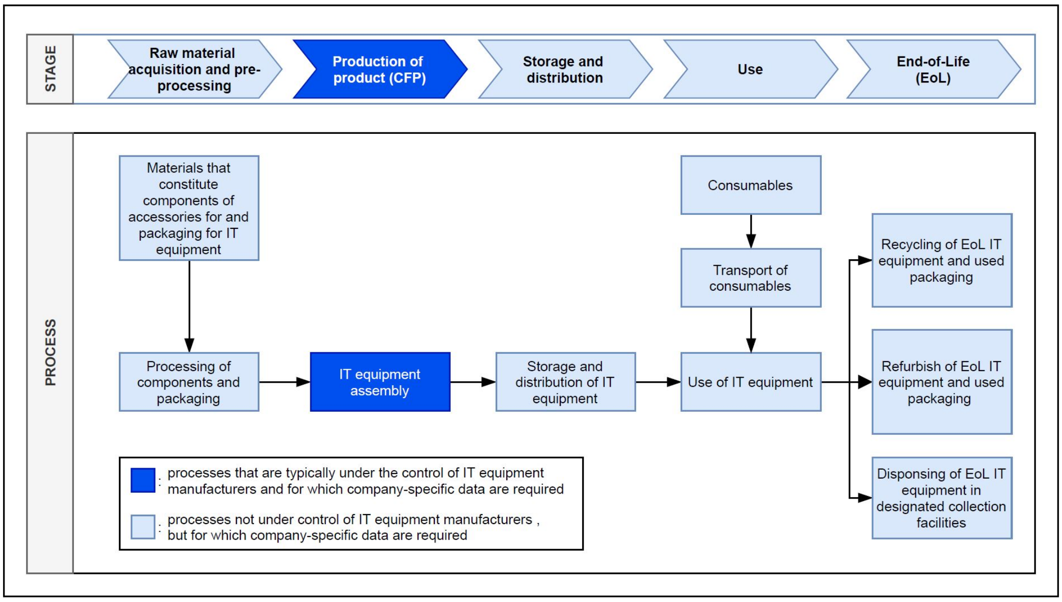


Figure 1.1: The AAU product variants life-cycle stages

In a complete life-cycle study, the inputs and outputs from each stage and the distribution ("transfer gates") between are quantified and mapped against a set of criteria (emissions, material resource, etc.) with their effects assessed to define the impacts of a product on different categories (i.e. Global Warming, Ocean Acidification, O-zone depletion etc.).

The project focus is to investigate and characterize the embodied carbon footprint of the AAU product variants, with an interest in quantifying the emissions related to the assembly activities, at the AAU Smart Production lab (delimited life-cycle stage).

1.1.1 The Product Emissions data through the Value chain

As depicted in Figure 1.2, the GHG emissions aggregates across the value chain, as a product passes through each stage. In order to account for the GHG emissions embodied in a product, the data needs to be collected and transmitted from supplier-to-supplier across the entire value chain. The data collection and transferability across the value chain presents a high degree of complexity and multiple challenges as the information is either not available or difficult to account for [4] [6].

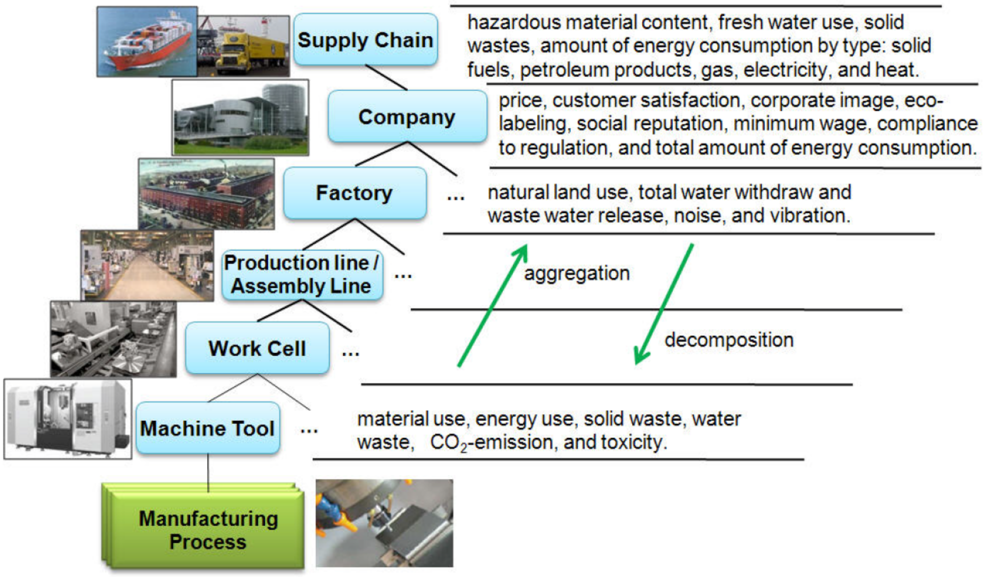


Figure 1.2: The aggregation of environmental impacts aggregated across the value chain *Feng et al.* [7]

The current methods for accounting and transferring GHG data of a product span from estimations to high-accuracy inventories come with an accuracy trade-off, which is due to (1) the lack of data from suppliers and sub-suppliers, (2) the prohibitively time consuming process and (3) the economic efforts required to collect the activity data from supplier to supplier.

Therefore the GHG data embodied in a product is non existent or usually estimated based on the industry-average data **secondary-data** and is rarely supplier-specific **primary data** [6].

1.1.2 Greenhouse Gas (GHG) Accounting

The GHG Protocol [8] categorizes the various emissions from the activities of an organisation into three main categories:

- *Scope 1* including the direct 'emissions from sources owned or directly controlled by the organisation'

- ***Scope 2*** - referred to as energy indirect GHG, are defined as *"emissions from the consumption of purchased electricity, steam or other sources of energy generated upstream from the organisation"*
- ***Scope 3*** - referred to as other indirect GHG, defined as *"emissions that are a consequence of the operations of an organisation, but are not directly owned or controlled by an organisation"*, including *employee commuting, business travel, third-party distribution and logistics, production of purchased goods, emissions from use of sold products, etc*

1.1.3 The Partial Carbon Footprint of a Product - Partial CFP

The partial carbon footprint (CFP) (ISO 14067:2018, 3.1.1.2) refers to the aggregated GHG emissions of a selected process or a group of processes in a product system, although only based on the selected stages of processes within the life cycle using a single impact category - climate change [9]. The impact category of concern for the project objective is *Climate Change*, as follows:

Impact category	Indicator	Unit	LCIA method
Climate change	Radiative forcing as Global Warming Potential (GWP100)	$kgCO_2e$	Baseline model of 100 years of the IPCC (based on IPCC 2013)

This provides an option to account for the activity data for processes within a life cycle stage, in a separate and modular manner. In the current case, the focus is on the assembly operations of products, as a sub-division of manufacturing stages.

According to European Commission PEFCR guidelines [10], the GHG emissions accounting and reporting of a product needs to follow the partially aggregated principle throughout the value chain, as depicted in Figure 1.3. The raw data from the *unit processes dataset* which a product needs to undergo throughout its life cycle is aggregated with other *aggregated process datasets*, from supplier tiers and sub-tiers.

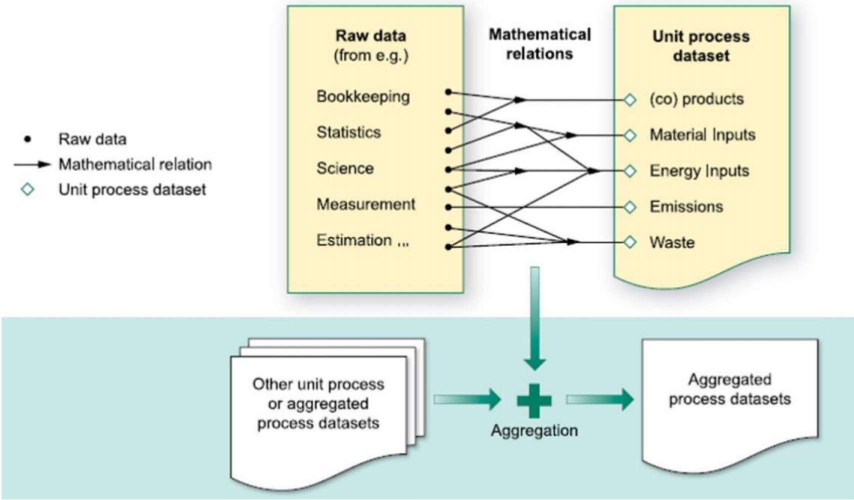


Figure 1.3: Current approaches to GHG accouting and aggregation of unit process dataset and an aggregated process dataset (taken as excerpt from the PECER guideance v6.3.2) [10]

1.2 The Motivation for the project

The rationale of embodying GHG inventory data into a product by technological means, is believed to improve both the collection of carbon emission data at the source of generation and support the transmission across the value chain. Thus throughout a product life cycle, the activity data and location-based emission factors could "follow" the product throughout the value chain, contributing to a more accurate and transparent GHG product data, as well as eventual risks of a company's supply chain.

The motivation of the project is to employ technological means to characterize the energy consumption profiles of manufacturing operations involved in producing or assembling various product variants. Along with this, partial carbon footprints (as explained in Section 1.1.3) are to be automatically generated based on product configuration.

This is envisioned to be achieved by developing a proof-of-concept to (1) monitor and quantify the energy used for the assembly processes, (2) calculate and aggregate the electrical energy emission data (kgCO2e/kWh) for the assembly processes, (3) ascertain the embodied emission data for the assembled product variants and (4) create a product configurator which shows an estimate of the embodied emission data for various product variants.

The empirical study is formulated as a case-study carried out on the FESTO assembly line, part of the AAU smart production lab facility.

1.3 AAU Assembly line at Smart Production Lab

The assembly line at AAU Smart Production Lab is a collection of process modules which perform an activity on a product. Currently used for educational purposes, the line assembles unusable (dummy) phones consisting of a bottom and upper housing part, a Printed Circuit Board (PCB) and fuses, as depicted in Figure 1.4.

Figure 1.5 shows the modular assembly line which comprises of workstations as independent and modular entities with line topology networking and controlling capabilities, responsible for routing the products using conveyor belts as well as powering and controlling various process modules, such as:

- Station 1 - Feeding process module: a unit dispenser which dispenses the back cover of the product
- Station 2 - Drilling process module: a drill unit which drills wholes into the back cover of the product
- Station 3 - Pick&place process module: a 6-axis robot with several sequential processes which assembles the PCB and fuse components onto the cover of the product
- Station 4 - Quality insurance process module: a vision system performing positioning and aligning checks
- Station 5 - Feeding process module: a unit dispenser which dispenses the top cover of the product
- Station 6 - currently without process modules, capable of routing the product using conveyors
- Station 7 - currently without process modules, allowing manual post-assembly activities

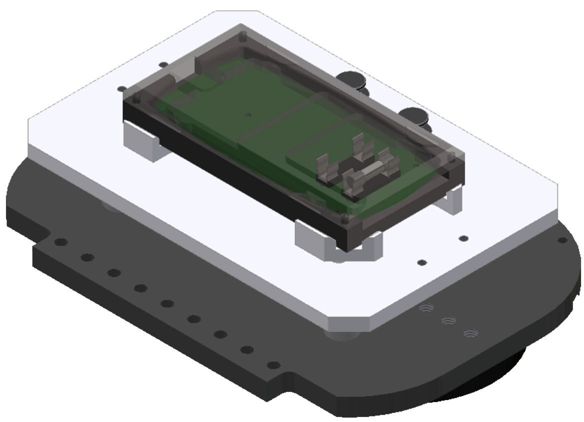


Figure 1.4: Carrier module with the assembled product (phone replica)

Figure 1.5: AAU Smart Production Lab

1.4 Initial Problem Formulation

In the quest of providing product environmental information data as a competitive-advantage strategy, the focus of this project is to create a proof-of-concept formulated as a product configuration system, which would connect the customer to the product variants and production capabilities. The solution aspires to automate the computation of product emission data, for which the amount of energy consumed in each assembly activity is converted and aggregated to the equivalent emissions ($CO_2 - eq.$).

As initial problems that could act as foundations for the analysis and the concept development phase, are formulated as such:

- How could the conceptualized solutions take basis in the AAU assembly line and translate the product-related manufacturing activities into product carbon footprint?
- Which methods are adequate for collecting the energy consumption data associated with the manufacturing activities at AAU assembly line?
- Which technological means could be used for energy consumption data collection?
- How could the environmental information about products and the associated manufacturing activities be compiled into ICT systems, such as product configuration systems?

Chapter | 2

Background, Research & Analysis

The current Chapter presents the investigation required to identify the equivalent carbon emissions associated with the studied product variants. The investigation has several areas of focus such as providing insight into the energy consumption related to AAU assembly activities, potential methods for energy monitoring, as well as the order processing which product configuration systems aspire to substitute. The overall objective of the analysis is to establish critical requirements for the conceptualized solutions presented in Chapter 4, taking basis in the initially formulated problem in Section 1.4.

To give an easier understanding of the chapter, the following overview comprised of the sections containing the the analysis information are briefly described:

- Section 2.1.1 presents the sources of emissions associated with the manufacturing activities, as main contributors to formulate the partial carbon footprint of the AAU assembly processes. Additionally, the the studied product variants are presented and the embodied carbon emissions are estimated using life-cycle inventories from relevant emission databases.
- Section 2.2 provides an insight into the methods for measurements for quantifying electric and pneumatic energy in industrial settings. Once the methods are established, the technology capable of quantifying the types of energy consumption are assessed and favorable choices are presented.
- Section 2.3 introduces a classification of product configuration systems and presents the analysis of the enterprise ICT system, which serve for the solutions ease of integration. Additionally, the section also describes the simulated order processing at the AAU assembly line, estimated and adapted from relevant literature study.
- Section 2.4 facilitates the analysis overview formulated in a summary, containing the key reflective points and the functional requirements, which are to serve as a foundation for the conceptualized solutions.

2.1 Analysis of the current Assembly Line

Since the AAU assembly line is the facility where the product is assembled, it makes the scope of the first analysis phase, for which several objectives are the focus of the investigation:

- Identify the source of emissions at the AAU assembly line and the energy consumption sources of manufacturing equipment associated with the assembling activities, presented in Sections 2.1.1 and 2.1.2.
- Investigate the assembly line process flow and define the points of consumption within the system boundary for which the consumption data is to be collected. The analysis phase, in Section 2.1.3.
- Define the product variants and estimate the product components embodied carbon emissions until the AAU assembly line, using life-cycle inventories from emission databases. The impact assessment and results are presented in Section 2.1.4
- Clarify the Global Warming Potential and emission factors which are intended to be used in computing the emissions resulted from the assembling activities. The clarification can be consulted in Section 2.1.5

2.1.1 Carbon Footprint Tracking in Industrial Activities

To quantify the embodied partial carbon footprint of the product variants, it is necessary to identify the source of emissions which typically arise in industrial activities. According to Greenhouse Gas Protocol reporting standard [4], the ***direct emissions*** could be obtained from direct monitoring of the emissions released to atmosphere (e.g. emissions from incinerator, fugitive refrigerant, etc.) and the ***indirect emissions*** from the activity data for which emissions occur at the generation point (i.e. emissions from purchased electricity).

A quantitative approach of relevant metrics for a process/activity that results in greenhouse gas emissions could include:

- Energy (e.g., Joules of energy consumed)
- Mass (e.g., Kilograms of a material used)
- Volume (e.g., Geometrical dimensions of product or amount of chemicals used)
- Distance (e.g., Meters/kilometers travelled)
- Time (e.g., Operation hours)

As the manufacturing activities involved in assembling the product variant do not have direct emissions associated with the manufacturing equipment, the scope of the analysis is oriented towards the indirect emissions, consequentially resulted from the energy consumption, as energy used by a machinery to perform a function (physical activity).

2.1.2 AAU Assembly Activities and the Contributing Sources of CO_2

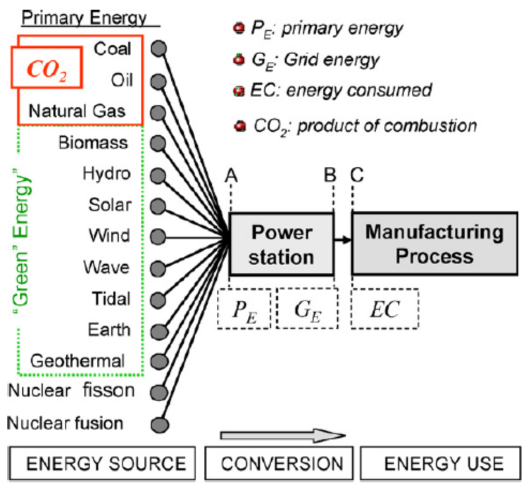


Figure 2.1: Energy generation and distribution, taken as excerpt from [2]

As identified by previous investigation, the carbon emissions are related to the energy consumed from the power grid, as the sources of energy production (i.e. power stations) which are fossil fuel based, release carbon emissions into atmosphere. This is represented in the Figure 2.1. As a consequence, the *indirect emissions* must be accounted for each activity that consume the electric energy in order to formulate the emission inventory for a product.

Collecting environmental emission data at the AAU assembly line is therefore related to both the amount of energy used and the sources of energy supply. The energy sources and the point of consumption of each manufacturing activity at the AAU assembly line represent the focus of the current section. These are analyzed in order to characterize the energy intensity for each assembly activity and ultimately formulate the emissions required for each product configuration.

The sources of consumption which contribute to ***indirect emissions***, are identified to be:

- **Electric energy** consumed to power the manufacturing equipment
- **Compressed air energy** consumed by the manufacturing equipment and powered by a compressor system. This energy is ultimately converted to electrical energy used by the compressed air system.

In a energy audit scenario, the energy related to the facility area (illumination, ventilation, etc.) would be allocated as overhead energy consumption, nevertheless this represents a delimitation of the project scope - of formulating the partial carbon footprint related solely to manufacturing activities, as stated in the delimitation section 3.3.

Similarly, the energy consumed by the branch and manual workstations, are neglected in the current investigation, as the related activities are not directly contributing to the assembly of the product variants (as stated in the project delimitations Section 3.3).

Once the sources of consumption are identified, the AAU assembly line is analyzed as an effort to systematically structure the sequence of operations involved in the assembly of the product variants. Along with this, the manufacturing equipment (resources) along with the type of energy consumed is tabulated, in Table 2.1.

	Task / Activity	Start time [s]	Completion time [s]	Resource	Energy source
Station 1 (S1) Feeder bottom housing	IN transport	0	8	Conveyor M1	Electrical
	Dispense bottom housing	8	6	Dispenser BH + stopper	Compressed Air
	OUT transport	14	3	Conveyor M1	Electrical
Station 2 (S2) Drilling	IN transport	17	8	Conveyor M2	Electrical
	Drilling process	25	10	Drilling machine + stopper	Electrical + Air
	OUT transport	35	3	Conveyor M2	Electrical
Station 3 (S3) Robot cell	Cell_in transport (conveyor1)	38	10	Conveyor M3	Electrical
	Cell_in transport (conveyor 2+bypass)	48	3	Conveyor M4 + bypass	Electrical + Air
	RFID_STOP	51	1	Conveyor M4 + stopper	Electrical + Air
	Cell_in bypass transport (conveyor 3)	52	9	Conveyor M5	Electrical
	RFID_STOP	61	1	Conveyor M5 + stopper	Electrical + Air
	Pick&place bottom cover	62	8	Robot	Electrical + Air
	Vision_orientation	70	9	Vision System + Robot	Electrical + Air
	Tool change for PCB	79	8	Robot	Electrical
	PCB pick&place	87	13	Robot	Electrical + Air
	Tool change for fuses	100	8	Robot	Electrical
	Pick&place_fuse 1	108	11	Robot	Electrical + Air
	Pick&place_fuse 2	119	8	Robot	Electrical + Air
	Tool change for b. cover	127	8	Robot	Electrical
	Pick&place bottom cover	135	11	Robot	Electrical + Air
	OUT transport	146	6	Conveyor M5	Electrical
Station 4 (S4) Quality control	IN transport	152	8	Conveyor M6	Electrical
	Quality control	160	2	Vision Q + stopper	Electrical + Air
	OUT transport	162	3	Conveyor M6	Electrical
Station 5 (S5) Feeder top housing	IN transport	165	8	Conveyor M7	Electrical
	Top dispenser process	173	4	Dispenser TH + stopper	Compressed Air
	OUT transport	177	3	Conveyor M7	Electrical

Table 2.1: The AAU assembly activities for full product variant, required resources and energy sources

2.1.3 The System Boundary: AAU Assembly Line Process overview and Flow

As presented in the activity diagram, shown in Figure 2.2, the operations are perfomed in an sequential manner and are dependent on the configuration of the product, meaning that for a configuration of the product with less components (i.e. without the fuses), the number of operations would decrease. As the objective is to define the points of consumption for the system boundary, each assembly activity is investigated.

The points of consumption were established to be:

- The station control and networking devices such as PLC, HMI panel
- The electric actuators for driving the conveyors
- The electric actuators of the process modules (e.g. drilling machine, robot)
- The pneumatic actuators of the process modules, the stoppers and the robot vacuuming for grippers used in pick&place operations

Once the assembly activities points of consumption were identified, the investigation leads to the product components-related information and their partial carbon footprint, embodied during the product life-cycle. This investigation is presented next, in Section 2.1.4.

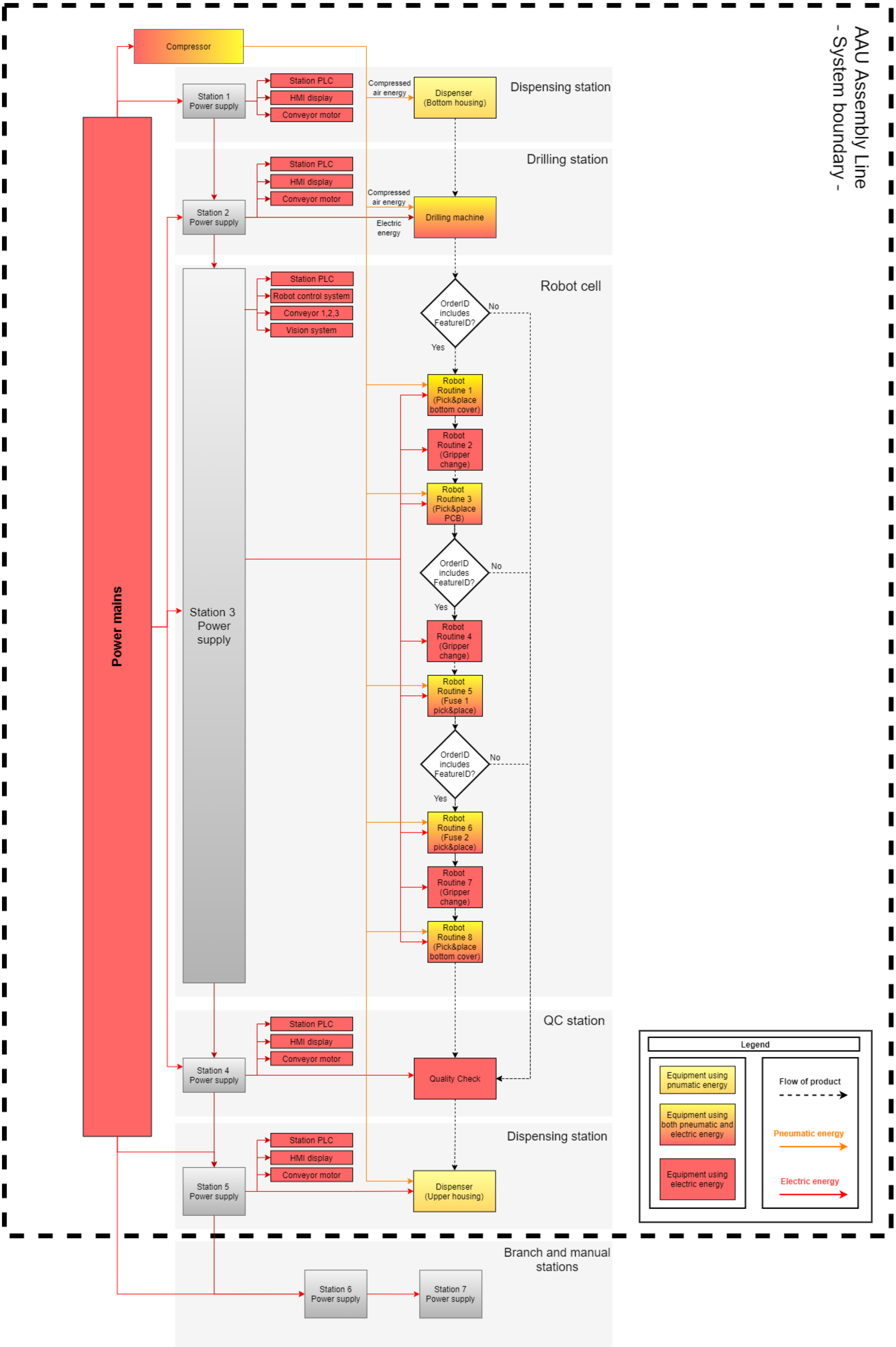


Figure 2.2: The AAU assembly CFP system boundary

2.1.4 AAU phone replica (PVM) and its partial Carbon Footprint (CFP)

The current section presents the analysis study done in order to define the conceptualized framework requirements of quantifying the embodied carbon footprint of the product variants, assembled on the AAU assembly line.

The definition of *a product* variant is defined by the combination of the components and their options/features, configured. Figure 2.3a depicts the Product Variant Master (PVM), used as a method for visualizing the Bill of Materials (BOM) as aggregation of modules, the "part-of" component dependency and the available properties/features.

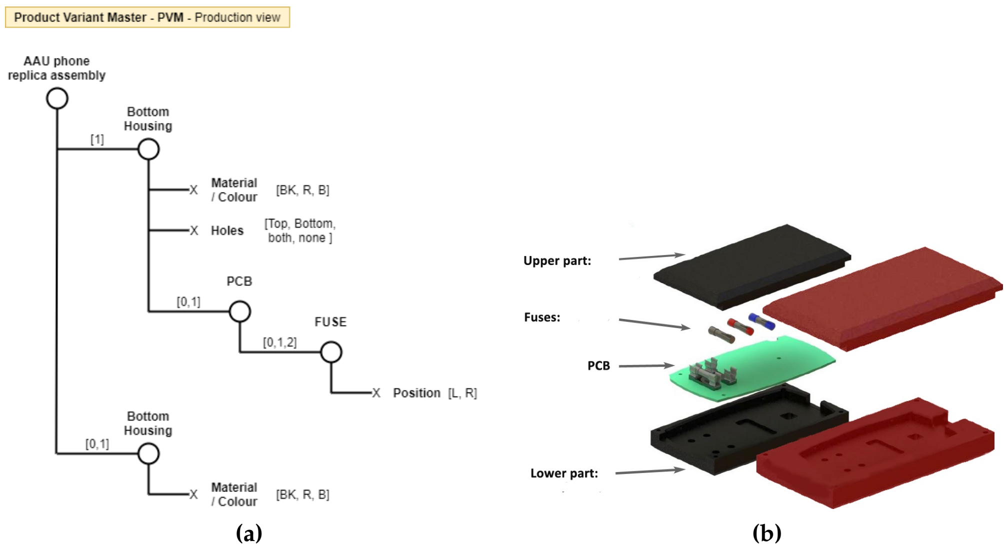


Figure 2.3: **(a)** The AAU phone replica Product Variant Master **(b)** The product components

The product comprises of two housing parts, each available in three different colours, a Printed Circuit Board (PCB) and two fuses, having a *slot-modular architecture*, meaning that each component has its own interface type for assembly. As shown in the Figure 2.3a, the bottom housing represents the main interface for product, as both the PCB and the top housing are mounted onto the bottom housing slots, thus creating a sequential dependency for assembly. Furthermore the PCB provides an interface itself for the fuses.

The AAU assembly line is capable of simulating drilling holes on the left and right side of the bottom housing part. As the holes do not constitute a component in the product variation, the drilling process is correlated with the fuse placement (left and right position), such that, if a fuse is configured for the left side, a left hole will be mapped in the configuration. This reflects a more realistic scenario of a product configuration based on its components, correlated with the manufacturing activities. The AAU phone replica can be seen in Figure **??** and the combinations of product variants is shown in Table 2.2.

i	Component	Combinations	Options
1	Bottom housing	2	Polycarbonate, Aluminium
2	PCB	2	with PCB, without PCB
3	Fuse	3	no fuse, fuse left, fuse right
4	Top housing	2	Polycarbonate, Aluminium
	Total: $\prod_1^4 n_i$:	**24**	

Table 2.2: Product variants combinations and options

As the project scope revolves around quantifying the partial carbon footprint of a selected stage in the product life-cycle, the focus is solely oriented towards the manufacturing processes at the AAU assembly line, and does not account for conducting an entire product life-cycle assessment, as described in the project delimitation, Section 3.3.

However, the motivation to replicate a product configurator behaviour of computing variations of the carbon footprint, an estimation of the amount of aggregated emission data embodied in the studied product, is preferred. This urges an estimation of previously accumulated emission data embodied into the components and their features/properties from the pre-processing stage of the product life-cycle. To obtain an estimation of the aggregated emission data, a life-cycle impact assessment was conducted, for the impact category of interest *Climate change*. The following subsection presents the analyses studied performed and relevant considerations.

Life-cycle Impact Assessment of product components

Goal and Scope definition In order to study the impacts of various processes which the components underwent throughout the life-cycle, it is important to establish the goal, scope, functional unit and reference flow for the product system. The goal of the study is to estimate the embodied emission data for various components, part of the AAU phone replica (the product).

The scope is to document an estimate of the environmental performance of various configurations of the studied product. To achieve this, relevant Life-cycle Inventory data sets are used to provide an inventory of emission data that could be correlated to the processes which a component underwent throughout the product life-cycle. The system boundary separately defined for each component follows a cradle-to-gate approach, meaning that the investigation includes the life-cycle stages from raw materials processing and manufacturing, investigating all GHG emissions until the point where the component arrives at the "gate" of the processing facility. The functional unit represents one piece of each component having various characteristics (material, geometry, weight). The reference flow is per configured product, having one of each component assembled.

Life Cycle Inventory (LCI) Analysis To simulate a real-case scenario and provide product environmental data in the conceptualized product configurator, the emission data aggregated before the AAU assembly facility, are estimated from published literature relevant to the specific component (secondary data).

To achieve this, the AAU replica phone components properties are changed from just colours to simulated materials, as expressed in Table 2.2. For this, a market study was conducted to estimate which materials could be associated with a mobile phone components and their properties, the components were analyzed in order to obtain the geometry and weight as these are the necessary inputs for the impact assessment study.

Firstly, all material and energy flows from raw material extraction until production processing were gathered and the CO_2-eq. was computed using emission factors from Ecoinvent database.

The bottom and top housing As the bottom and the top housing present similarities both in geometry, functionality and materials, it was decided that the estimation the carbon footprint embodied into the components are nearly identical, thus they are both represented as reference products in the life-cycle study. The functional unit chosen was per single component, weighing 65,5 [gr.] for the bottom housing and 53,4 [gr.] for the top housing. The functional unit covers the production processes involved in bringing the raw material into the product form, used in assembling processes at AAU.

This includes the aggregated emission data for the processes from raw material extraction until delivery at the location of pre-processing facility. The embodied equivalent emission data ($kgCO_2 - eq.$) computed during the impact assessment stage are shown in Table 2.6.

- **Polycarbonate:** To simulated the processing stage, which brings the plastics into the current geometry, the embodied emission data for the injection molding process was added, as shown in Table 2.3.
- **Aluminium:** The production of aluminium is highly energy intensive, as many processes are required to bring the raw materials (alumina, bauxite and other additives) into cast ingots. The data sets chosen to represent this include material and energy related to the alloy production and casting, scrap and primary metal input, preheating, induction melting, alloying, degassing, water use and ingot casting. Additionally, the data sets includes waste treatment and onsite wastewater treatment. To bring the material into final shape (housing geometry), a milling process is added to the simulation model, as shown in Table 2.3.

Component	Amount [gram]	Chosen I/O data set	Included activities	Data set reference
Bottom and top housing - Polycarbonate	Bottom: 65,5 Top: 54,8	Polycarbonate {RER}| production | Conseq, U	Production by interfacial polycondesation out of phosgene and bisphenol A	Source: 26418_8bb9d304-77dc-4f1e-946a-2ec945312e9c_e0d6f217-d1e3-4d5d-8b8a-b13c846d4ad6.spold UUID: 8bb9d304-77dc-4f1e-946a-2ec945312e9c
		Injection moulding {RER}| processing | Conseq, U	1 kg of this process equals 0.994 kg of injection moulded plastics	Source: 22044_a013b683-6fff-4d61-8545-e20bdff7702a_68d6dfcf-2089-4586-9bbf-ad75591105cf.spold UUID: a013b683-6fff-4d61-8545-e20bdff7702a
Bottom and top housing - Aluminium		Aluminium alloy, metal matrix composite {RoW}| aluminium alloy production, Metallic Matrix Composite | Conseq, U	Production of aluminium slab is used as the main aluminium bearing input (75-80%). Scrap aluminium used as input up to 20-15%	Source: 28696_23b3d10d-2e49-4796-813b-3649e634b9d6_9c78fb2b-13ba-46ab-8e5c-7996d9526938.spold UUID: 23b3d10d-2e49-4796-813b-3649e634b9d6
		Aluminium removed by milling, average {RER}| aluminium milling, average | Conseq, U	Reference for milling an average assumption 0.23kg of material removed per kg of final product	Source: 18454_548701ce-00c8-435c-9118-6850cc59cb49_76736f35-6812-4b73-967d-010efeda851f.spold UUID: 548701ce-00c8-435c-9118-6850cc59cb49

Table 2.3: Chosen LCI data set to represent the AAU Bottom and top housing components

The Printed Circuit Board (PCB) Following a similar cradle-to-gate approach, the emission data until the finished product was estimated using a simulation model in SimaPro software, using the Ecoinvent 3 database [11]. For the system model, a LCI data set was chosen from the electronics unit processes which represents the production of a 6-layer FR-4 printed wiring board prepared for surface mounting of components.

The functional unit chosen was per single component, with a surface area of $5.83E^3$ [mm^2] (106 mm x 55 mm). The functional unit covers the materials and energy flows as inputs and output from raw materials, infrastructure, energy consumption, emissions to air and water and waste. The data set is represented in Table 2.4 and the results from the impact assessment are tabulated in Table 2.6.

Component	Dimensions [mm]	Chosen I/O data set	Included activities	Data set reference
Printed circuit board (PCB)	106 x 55	Printed wiring board, for surface mounting, Pb free surface {GLO}| production | Conseq, U	"Substrate preparation, imaging, exposure, etching, sandwiching, activation and accelaration steps as well as copper plating, cleaning, oxidification, dry vacuum lamination, micro etching, surface finishing."	Source: 26529_cd42b0da-9a2f-45dc-a99a-2f87-af540739_65cf8186-2a0d-4271-b7ee-62c9f5d5100c.spold UUID: cd42b0da-9a2f-45dc-a99a-2f87af540739

Table 2.4: Chosen LCI data set to represent the AAU PCB replica

Fuse 1 and 2 To simulate similar characteristics to a mobile phone, the fuse components are modeled as passive electronic components using a life-cycle inventory (LCI) data set, as tabulated in Table 2.5. The chosen data set represents the production of unweighted mean value of connectors, capacitors, inductors and resistors.

This represents an estimated value of a mix of electronic components, present in the mobile phones. For a functional unit of one piece, weighing 1.4 grams, the product model will show an estimation of the materials and energy flows as inputs and output from raw materials, infrastructure, energy consumption, emissions to air, water and waste.

Component	Amount [gram]	Chosen I/O data set	Included activities	Data set reference
Fuse	1,4	Electronic component, passive, unspecified {GLO}| production | Conseq, U	Production of 1 kg of passive electronic component, for all those cases, where no information is given about the passive component type. It is an unweighted mean value of: connectors, capacitors, inductors and resistors data sets	Source: 21164_fc34a769-486a-4179-8162-c93ae0e206c2_4e252b55-fb08-4447-8391-d09e8bbb0238.spold UUID: fc34a769-486a-4179-8162-c93ae0e206c2

Table 2.5: Chosen LCI data set to represent the AAU fuse component

Impact Assessment To ensure a consistent evaluation of the embodied emissions for the product components, the product systems had a consistent functional unit of one phone replica consisting of one of each component and a reference flow of the amount of material and energy required to accomplish the functional unit. The impact assessment study was created containing the collection of the unit processes with material and energy flows from the chosen data sets, computed using emission factors from Ecoinvent 3 database as described in Tables 2.3, 2.4 and 2.5.

Using the *ILCD 2011 Midpoint V1.03* method[1] would provide the characterisation factors for impact assessment as recommended by European Commission, Joint Research Centre [12]. As the current project study is focused on quantifying the equivalent $kgCO_2$ emissions, the impact category of interest is *Climate change*, with a IPCC 2007 Global Warming Potentials for various greenhouse gasses over a time horizon of 100 years, as previously introduced in Section 1.1.3 and described in more detail in Section 2.1.5.

Table 2.6 presents the estimated embodied emission data based for various product components.

Component	Property	Characteristics	kg CO_2 eq.	Method	Impact category
Top housing	Polycarbonate	54,8 gr.	**0,48**	ILCD 2011 Midpoint+ V1.10 / EC-JRC Global, equal weighting	Climate change
Bottom housing	Polycarbonate	65,5 gr.	**0,59**	ILCD 2011 Midpoint+ V1.10 / EC-JRC Global, equal weighting	Climate change
Top housing	Aluminium	54,8 gr.	**1,08**	ILCD 2011 Midpoint+ V1.10 / EC-JRC Global, equal weighting	Climate change
Bottom housing	Aluminium	65,5 gr.	**1,32**	ILCD 2011 Midpoint+ V1.10 / EC-JRC Global, equal weighting	Climate change
Printed circuit board (PCB)	Standard multilayer Pb free surface	106 mm x 55 mm	**2,18**	ILCD 2011 Midpoint+ V1.10 / EC-JRC Global, equal weighting	Climate change
Fuse	Electronic component (passive)	1,4 gr.	**0,083**	ILCD 2011 Midpoint+ V1.10 / EC-JRC Global, equal weighting	Climate change

Table 2.6: The impact assessment results for various components

Thus, these Figures will become an integrated part of the product configurator to emulate the embodied emission data correlated with the technical product information (e.g. Bill of Materials). These values will be aggregated with the emissions resulted from the AAU assembly activities, as presented in the next Section 2.1.1.

2.1.5 Global Warming Potential (GWP) and Emission factors

The Greenhouse Gasses [2] have different warming effects on earth and are therefore characterized by their ability to absorb energy (called *radiative efficiency*) and their ability to remain in the atmosphere (*"lifetime"*). In order to enable comparisons of their impacts, they are compiled into factors - the *Global Warming Potentials (GWP)*.

[1] An LCIA method is LCIA method is a collection of impact categories that aims to have a broad coverage of environmental issues

[2] (GHG is an umbrella term for defining groups of gasses such as *CO*2, *CH*4, *N*2*O*, *CFCs*, *HFCs*, *HCFCs*, *PFCs*, *SF*6)

The *Intergovernmental Panel on Climate Change* (IPCC) issues scientific reports for global references which allow common unit of measure. The most common used by the industry and policymakers is the 100-year time horizon GWP. Thus, for the current project scope, the GWP values for 100-year time horizon will be used. The GWP factors extracted from the IPCC 5^{th} assessment report can be consulted in the appendix A.1.

The *GHG emissions factors* represent that GHG emissions per unit of activity/process (e.g. per kWh). The activity data is multiplied with an *emission factor*. This results in the GHG emission data based on the activity intensity, and are calculated using the following formula:

$$\begin{aligned} kgCO_2e = ActivityData \quad [kWh] \quad \times \quad EmissionFactor \quad [kgCO_2e/kWh] \\ \times \quad GWP \quad [kgCO_2e/kgGHG] \end{aligned} \tag{2.1}$$

The emission factors are estimates of the amount of GHG emissions used in a particular industry, or product category, derived nationally based on the emission intensity of geographic regions (e.g. a region could supply energy from a power plant by burning fossil fuel or other regions based on wind energy or other renewable energy sources). This results in different emission intensities.

The data accuracy is minimized if the emission factors are used from emission factors data sets, as these typically represent industry average data, which is usually the case of a typical Life-cycle Inventories, used in LCA studies. As for the current project scope, the ambitions are to make use of the emission factors provided as data-as-a-service, via Application Programming Interface (APIs). This enables a more precise (based on geographical region) and up-to-date information.

The Energy Data Service, provides APIs which contain data sets as (nearly) updated history for the CO2 emission factors from electricity consumed in Denmark (g/KWh). As an additional service, a 8-hours prognosis is made available with a resolution data of 5 minutes, and a updated frequency of 15 minutes [13]. The forecast relays on the combined gCO2e/kWh for each each power plant in Denmark, being updated based on the daily power plant production schedules.

Functional Requirements Therefore, the carbon footprint for the AAU assembly activities will be computed using the up-to-date and regional electricity emission factors data sets, provided by the Energy Data Service [13]. It is believed that this would enable a more up-to-date estimation of emissions intensity characterization of the AAU assembly processes. The entire list of functional requirements can be consulted at the end of the analysis Chapter, in Section 2.4.1.

2.2 Industrial Power and Energy metering in Manufacturing

Manufacturing facilities operations imply the consumption of significant amount of electrical energy being primarily used to power motors, various machine tools and compressors. As the preliminary analysis has shown (Section 2.1.2, the AAU assembly line consumption sources are the *electric energy* - as direct source to power the electrical actuators and *compressed air energy* - consumed by the pneumatic actuators. The compressed air energy ultimately is converted to electrical energy used by the compressed air system.

In order to ensure adequate methods and technology means to quantify the amount of power consumed by the AAU assembly processes, an assessment was performed to establish the methods of measurement for *electric energy - Section 2.2.1* and *compressed air energy - Section 2.2.3*.

Once the methods for measurement were assessed, the analysis leads to the technology assessment step. To quantify the amount of power consumed, different energy sensing equipment is necessary for conducting the assessment. Section 2.2.2 and Section 2.2.4 introduces the technology choice analysis of the industrial sensing equipment and presents considerations in form of advantages and disadvantages.

2.2.1 Methods of Measurement – Electric Energy

Active, Reactive and Apparent Power Studying the transmission of electrical energy and the behaviour of AC industrial equipment often encapsulates the terms of *active, reactive* and *apparent power*, which apply to steady-state alternating current circuits, in which voltages and currents are sinusoidal [14].

The analysis begins with the concept of *active power* which is the energy transferred to a resistive load such as transformers, motors and is dissipated to produce useful work. For purely resistive loads the principles of Ohms Law applies, which states that the current drawn is equal to the voltage divided by their resistance and that the power is the product of the current and voltage that flows through a system terminals, measured in Watts [14]. This is depicted in the Figure 2.4
However industrial equipment such as drills, refrigerators, arc welders are devices that create internal magnetic fields where certain amount of energy is taken in and then released back into the supply. The power term used for this types of loads is which distinguishes from active power due to its oscillating between negative and positive values, as seen in Figure 2.5.
Reactive power is a measure of no useful work, and represents the energy that oscillate back and forth to a load from the supply showing negative values when going back to the supply mains. The reactive power is measured in Volt-Ampere-Reactive (VAR). This is a typical behaviour for industrial equipment having inductive com-

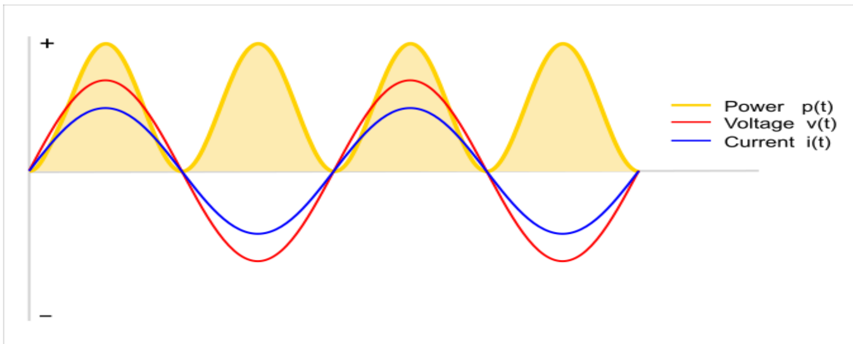


Figure 2.4: *"Voltage and current phase relationships in a resistive load"* taken as an excerpt from [15]

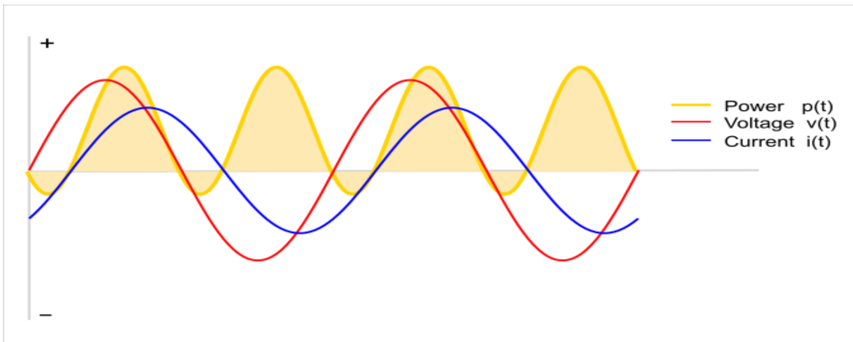


Figure 2.5: *"Voltage and current phase relationships in a partially reactive load"* taken as an excerpt from [15]

ponents such as motors or capacitive components (e.g. arc welders) [14]. The positive value for power denotes the energy flowing towards the inductive load and the negative is the energy flowing back to the supply. Studying the loads that absorb both the active and reactive power leads to the definition of the third term, *apparent* power.

In an AC circuit, *apparent* power is the measure of the active and the reactive power. In order to simplify the oscillating negative-positive behaviour of signal amplitude (peak-to-peak, peak), the Root-Mean-Square (RMS) can be computed, to obtain the averaged power delivered and used in a system, given by the following equation 2.2.

$$Apparent \quad power = U_{RMS} \quad \times \quad I_{RMS} \tag{2.2}$$

Apparent power can be more practically determined over a time averaged value of cycles, by instantaneous measurements of single phase AC electricity, namely Root-Mean-Square (RMS). This is achieved by computing the product of the Root-Mean-Square (RMS) Voltage and the Root-Mean-Square (RMS) Voltage values, measured in units of Volt-Ampere (VA).

A voltage RMS value is computed as the square-root of the mean square of the instantaneous voltage values measured and averaged over a cycle. Similarly, the current RMS value is computed using the instantaneous curent values. The discrete time equation 2.3 for calculating voltage and current RMS values is:

$$U_{RMS} = \sqrt{\frac{\sum_{n=0}^{N-1} u^2(n)}{N}} \quad and \quad I_{RMS} = \sqrt{\frac{\sum_{n=0}^{N-1} i^2(n)}{N}} \tag{2.3}$$

Where,

- $u(n)$ - sampled instance of the instantaneous voltage $u(t)$
- $i(n)$ - sampled instance of the instantaneous current $i(t)$
- N - number of samples

As nominal value of the voltage in all public low-voltage networks in Europe is delivered at a relatively stable and constant value of 230V (+10% -6% in the EU) [16], it is possible to approximate apparent power without making a voltage measurements and only measure the current of single phase AC equipment. This simplified approach will give an approximation of the power consumed and does not reflect an accurate result. However for the current objective, it was agreed with the project stakeholders that only measuring current of single phase AC and considering a constant voltage of 230 V, would give the desired estimation of power consumption.

Thus, for proof-of-concept the energy consumed by the manufacturing equipment at AAU will be approximated sensing only single phase AC current using a fixed value of 230 Volts to approximate the power.

Once the measurements to be recorded are established, the analysis leads to the part for investigating which technology is capable of sensing electrical power supply, required by the manufacturing equipment. In the next section, the various sensors commonly used in industrial applications are investigated, based on literature studies.

2.2.2 Choice of Technology for Electrical Energy Sensing equipment

To quantify the amount of power consumed, different sensing equipment is necessary for conducting the collection of data. The current section introduces a short description to the possible sensing equipment and presents considerations in form of advantages and disadvantages.

As literature has shown [17] to quantify the power consumption in industrial settings involves measurements of both the voltage and current. However for the current objective, it was agreed with the project stakeholders that measuring current only and considering a constant voltage of 230 V, would give the desired estimation of power consumption. In industrial settings the most frequently used equipment for current sensing is performed using *shunt resistors*, *hall-effect*, and *induction* [17].

The desired criteria for the choice of technology is related to:

- The **capability of sensing** sing-phase AC current with a rate input current from 0 to 16 Ampere.
- The **capability of interfacing** with a micro-controller for rapid prototyping such as Arduino, ESP, Raspberry Pi.
- The **ease of operation** as it is desired that the sensor can be easy and fast to mount at terminal equipment, without the need to interrupt the power or make modifications to the equipment
- The **cost of technology** as the budget pose constraints to the purchase of sensing equipment. As the project objective is a proof-of-concept, the approximations and lower costs are rather favorable in a accuracy-cost trade-off.

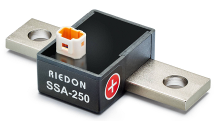


Figure 2.6: Shunt resistor sensor, taken from [18]

Shunt resistors The principle of operation of shunt resistive sensors is intrusive, where the sensing unit comprising a resistor is mounted in the path of the current flow, creating a voltage drop. For a known resistance, the measured voltage drop is used to calculate the current, following the Ohm's law (I = V/R).

Considerations The advantages of using such sensor are acknowledged in low-power electronics as otherwise used in high power equipment, the resistor would generate a prohibited power loss. An important disadvantage is that if a shunt resistor is used in high power applications and dissipation in the resistor is desired to be kept low, the voltage drop is small, which additionally requires amplification, inducing a higher cost and size of sensing equipment [17]. As a consequence, the shunt resistors are not suitable to quantify the power consumption at the AAU assembly line.

Figure 2.7: Hall-effect sensor, taken from [19]

Hall-effect sensors The hall-effect sensors components are typically a magnetic core, a semiconductor hall element (chip) and a signal conditioner which, for a given current flow in a conductor (cable) that passes through the magnetic core, a magnetic flux is created. The hall element captures the magnetic flux and generates a potential difference (voltage) proportional to the flux density of the magnetic field [17].

Considerations Since the voltage induced in the hall element is small, it requires amplification, which increases the cost of equipment. The hall-effect sensors are sensitive to the electrical environment and location, as the magnetic hall-effect device could capture noise by nearby currents. Moreover the voltage level significantly temperature-dependent, which requires particular excitation approaches in signal-conditioning [20]. These factors influence both the ease of operation and costs, which makes the hall-effect sensors an undesirable choice.

Figure 2.8: Current transformer sensor, taken from [21]

Inductive sensors Inductive sensors such as current transformers are the most frequently used in current sensing applications because the direct proportionality between the output voltage and the primary current and because of the ability to "step down" / reduce the current levels. This is achieved by the sets of coils (turn of windings) which captures the current inflow passing the conductor (cable) and induces a current proportional to the number of windings, thus achieving a predetermined ratio [17] [20].

Considerations As the current is reduce internally by the windings, the output levels can be directly captured by the the ADC and micro-controllers, without the need for additional conditioning equipment. Due to this principle of operation, both the cost and ease of operation are minimized. Additionally, for a split-core type, the sensing unit can be easily installed (clamped on a cable) in an non intrusive way, without interrupting the power or making modifications to the terminal equipment. These characteristics makes the current transformers (CT) sensors a favorable choice for the project objectives [17].

The chosen technology together with the product model is shown in Table 2.7, and the model specifications can be consulted in the product data sheets [22].

Chosen technology	Product model	Characteristics	Interfacing with microcontroller	Ease of operation	Cost of technology
AC current transformer (CT) sensor	SCT-013-000	Input rate: 0-100A Output: 0-50mA	Standard three-core: 3.5mm audio plug	Non-intrusive. Clamp-on, easy mount	Reduced cost. No need for additional signal conditioning equipment.

Table 2.7: Chosen technology to capture the single-phase AC current

2.2.3 Methods of Measurement – Compressed Air System

In manufacturing operations which use pneumatic systems, the compressed air used by the pneumatic actuators to produce useful work is typically supplied through a complex network of pipes, filters and regulators air-dryers and air vessels as expressed in Figure 2.9a.

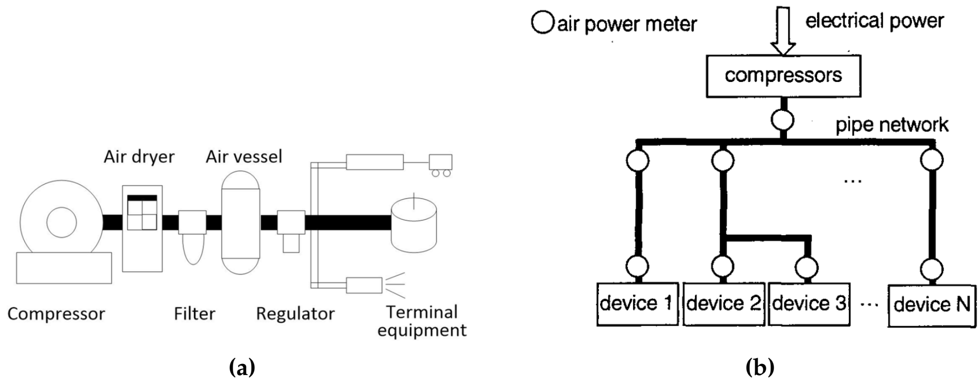


Figure 2.9: (a) *"A typical compressed air system"* taken from [23] **(b)** *"Setting of air power meter in a factory"* taken from [23]

In manufacturing facilities, compressed air systems are decentralized, meaning that the compressor system is usually separated from the point of consumption and the air is supplied to the terminal equipment through a network of pipes.

Therefore, a energy audit could be done at various points of the compressed air system, depending on the desired results. As Figure 2.9b depicts, the investigation points for quantifying energy consumption of compressed air including:

- At compressor point at the output pipe of compressor, typically used for anomaly detection including air leakages and contamination.
- At the main supply pipe, used for monitoring the total consumption of compressed air in a manufacturing facility
- At various points in the pipe network, to investigate air energy distribution at different locations (pipe leak detection)
- At device level, to quantify the energy consumption of a pneumatic actuator when engaged to do useful work.

For the current project scope, it was agreed with the project stakeholders that both the expenses for investment and prohibited time used in assessment, limits the parts of the energy audit to an estimation scenario. The estimation implies that a flow sensor is applied to the application equipment (process module) to quantify the the pneumatic power delivered at the device level. From that point, the electric energy supplied to the compressor is estimated using literature studies, for which the transmission losses and efficiency of the system are estimated and accounted for.

The estimation processes is described in the following section including the analysis of the energy flow in the pneumatic system at the AAU Smart Production lab facility. The pneumatic power of consumed air flow consists of two parts:

- ***The pneumatic transmission power*** which represents the flow of the energy required to push the air flow through the system from upstream (compressor) to downstream (application equipment) [24].
- ***The pneumatic expansion power*** which represents the flow of the energy applied to yield mechanical useful work, under atmospheric conditions [24].

The measurement of pneumatic power can be done by measuring *pressure, temperature* and *flow rate* of air. For this three different types of sensors are required, namely a flow rate sensor, pressure sensor and temperature sensor. The measured values can be compiled to calculate air power of flowing air expressed in Watts, similar to the unit used to express electric power [24] [23].

$$P = P_t + P_e = p_s * q_v * [ln\frac{p_s}{p_a} + \frac{k}{k-1}(\frac{T - T_a}{T_a} - ln\frac{T}{T_a})] \tag{2.4}$$

where,

- P_t - The pneumatic transmission power
- P_e - The pneumatic expansion power
- p_s - The system supplied pressure
- p_a - The atmospheric pressure
- q_v - The volumetric flow rate at standard conditions
- k - Specific heat ratio, for air $k = 1,4$
- T - Supplied air temperature
- T_a - Atmospheric temperature

This shows that pneumatic power is temperature dependent and with a higher temperature, a higher power is achieved. Nevertheless, air temperature is conditioned by air dryers and coolers to eliminate the condensation of water, which damages the pipes and application equipment. Because of this, the temperature output from compressor will return to atmospheric temperature when the air reaches the application equipment, as it flows through the dryer, vessel and pipe network [23] [24]. Thus, the transmission power due to temperature is lost during transmission. Therefore, temperature can be neglected in the calculation of pneumatic power [25]. When the air temperature and atmosphere temperature are the same, the the pneumatic power can be obtained from the fluid power using a simplified equation:

$$P[W] = p_s[Pa] * q_v[m^3/s] \tag{2.5}$$

Power losses Common methods for analyzing the in compressed air system imply four parts: *production, clean, distribution* and *consumption* of air. In each stage, the pneumatic power is affected by system losses. The losses present in such system are related to the irreversible thermodynamic processes [24]:

- The mechanical irreversible process, cause by internal friction (between compressor motor internal components) and external friction (between pipe walls and air flow).
- The thermal irreversible process, caused by the heat dissipation between the compressed air and surroundings, typically occurring after compression, between after-cooler and dryer .

Compressed Air system efficiency As literature suggests, a comprehensive assessment of the system efficiency implies measuring the differences in power at each component and calculating the component efficiency. Once each component efficiency is found, the total system efficiency can be computed as the product of efficiencies of all components at each power distribution stage [25]. The efficiency at each stage of the power distribution in a compressed air system can be computed by the ratio of the power output and the power input:

$$\eta = \frac{P_{out}}{P_{in}} * 100\% \tag{2.6}$$

Air production The compressed air energy supplied to the application equipment is provided by the compressor's electric motor which transforms the electrical energy into pneumatic power, transmitted as flow of compressed air. The efficiency of the compressor influences the amount of electrical power consumed and is computed as the ratio between the electrical power supplied and the of pneumatic power output.

Type	Capacity (N·L/s) (0.8 MPa)	Specific energy (kW·h/m^3)	η_{cp} (%)
Piston	<20	0.133	39.6
	20–200	0.095	55.4
	200–2000	0.072	73.1
Vane	<20	0.125	42.1
	20–200	0.100	52.7
Screw	<20	0.116	45.4
	20–200	0.100	52.7
	200–2000	0.092	57.2
Centrifugal	400–1000	0.091	57.9
	1000–2000	0.083	63.4

Figure 2.10: "Some typical compressor features", extracted from [25]

Due to the equipment limitations to measure the pneumatic power output, it was agreed with the project stakeholders that the compressor efficiency is estimated based on literature studies. As shown in Figure 2.10, several characteristics of typical compressors available on the market are tabulated. The efficiency of compressor types vary from 39.6 % to 73.1 %, depending on the motor power and capacity.

The AAU compressor was identified to be a *screw type*, manufactured by Atlas Copco. The compressor model is AQ22VSD [26] with a rated capacity ranging between 17.1 - 64.5 [l/s] supplying 8 [bar] of pressure. Thus a rated efficiency is assumed to be $\eta_{cp} = 52,7\%$, based on literature suggestion [25] correlated with the capacity of the compressor at AAU:

Air cleaning and filtering Considering that motor influence only a part of the overall efficiency of the system, the air cleaning and distribution also account for computing the total consumption. Thus, the power consumption used by the dryer is added to the power consumption of the compressor. This is done by computing the coefficient K_{dy}, as suggested in [25]:

$$K_{dy} = \frac{1}{\eta_{cp} * (P_{supply}/P_{out}) + 1} \tag{2.7}$$

where P_{supply} is the dryer electrical power supply and P_{out} is the output pneumatic power computed using equation 2.5. However, due to the equipment limitations to measure the pneumatic power at the dryer output, it was agreed with the project stakeholders that the dryer efficiency is estimated to be $K_{dy} = 0,96$ based on the suggestion in [25], correlated with the applicable compressor power.

Moreover, the power loss in the filtering stage, is computed due to the pressure loss at the filter. At AAU, the filter is integrated in the air dryer - model FD70, having a pressure drop $\Delta p_{fl} = 0,22[bar]$ at full flow (70 l/s), given by the manufacturer in the product catalog [27]. According to the same literature study [25], the power transfer efficiency of the filter (η_{fl}) is computed as:

Type	A	B	C	D
Applicable compressor (kW)	2.2	15	75	370
Assumed η_{cp} (%)	40	50	50	60
K_{dy}	0.90	0.96	0.97	0.97

Figure 2.11: "K_{dy} of some refrigeration dryer", extracted from [25]

$$\eta_{fl} = \frac{P_{out}}{P_{in}} * 100\% = \frac{ln((P_{in} - \Delta P_{fl})/P_{atm})}{ln(P_{in}/P_{atm})} * 100\% \tag{2.8}$$

where ΔP_{fl} represents the power of the pressure loss at full flow. For a inlet pressure of 8 bar, the power transfer efficiency of the filter η_{fl} rounds 98%. This Figure can be validated by the above mentioned literature study, as the authors claim that the computational efficiency of the filter in the market ranges between 95% and 99%[25].

To obtain the overall system efficiency (η_{ovr}) at the cleaning and filtering, the overall stage efficiency is computed as the product of the dryer coefficient K_{dy} and energy transfer efficiency of the filter (η_{fl}), such as:

$$\eta_{ovr} = \eta_{fl} * K_{dy} \tag{2.9}$$

Thus, the efficiency for the air transmission in cleaning and filtering stage is computed to be the product of the dryer coefficient and the filter efficiency rounding η_{ovr} = 94%, as shown in Table 2.8.

Air distribution As literature suggests [25], in the pipeline distribution, there are two factors that cause power loss: the *pressure loss* and *air leakage*. Pressure losses occur at the joints of the piping system and in the internal friction of the pipes. Leaks occur in piping connections, hose fittings, valves and are typically investigated by quantifying the flow of air and pressure drop at various locations, as discussed at the beginning of this section. This presents a limitation of the project scope, due to the prohibitively time consuming activities and expenses in equipment involved. Therefore, the losses in the pipeline network were agreed with the project stakeholders to be estimated based on literature studies.

The common allowable amount of air leakage in industrial facilities are recommended to be less than 5%, however, in reality, literature suggests that the proportion is as high as 10% - 40% [25]. As the system is regularly maintained and inspected by specialized technicians, it is safe to assume that the power losses in the pipe network distribution at AAU are not higher than 10%, thus an efficiency of the transmission power η_t is estimated to be at about 90%.

Based on the above analysis, the efficiencies of the stages until the point of consumption are summarized and tabulated in Table 2.8, using the assumptions details, adapted based on the literature suggestion [25].

Stage	Efficiency notation	Efficiency [%]	Assumption details
Production	η_{cp}	52,7	For screw type with a capacity between 17.1 - 64.5 [l/s]
Cleaning & filtering	η_{ovr}	94	dryer: $K_{dy} = 0,96$ ∣ filter: η_{fl} = 95%
Transmission	η_t	90	pressure loss and air leaks: 10%
Total	η_{tot}	**45**	**Computed as the product of each stage efficiency**

Table 2.8: Assummed compressed air system efficiency at AAU

Table 2.8 summarises the estimated efficiencies of the entire pneumatic system at AAU. This is done in order to compute the $kgCO_2 - eq$. of the amount of electric energy consumed by the pneumatic system when engaged in assembling the product variants, as stated in Section 2.1.2. Once the amount of power used at the device level is known (P_{device}), the power consumption at the compressor side could be established by computing the required power $P_{required}$ which the compressor system uses:

$$P_{required} = \frac{P_{device}}{\eta_{tot}} * 100\% \tag{2.10}$$

The consumption point at terminal equipment (process module) is to be measured using appropriate sensing equipment in order to characterize [3] the amount of energy required for each assembly activity associated with a product component. In order to ensure that appropriate equipment is used, various sensing equipment are analyzed and presented in the following section.

[3] The energy consumption results can be consulted in Section 4.1.3

2.2.4 Choice of technology for Pneumatic Energy Sensing

To quantify the pneumatic power, it is necessary to collect the pneumatic energy required to perform the various assembly activities at the AAU assembly line. The current section presents the various technologies capable of sensing the pneumatic energy of compressed air and presents considerations in form of advantages and disadvantages. At the end of the section, the most suitable technology is chosen.

As discussed in Section 2.2.3, the air power is proportional to flow rate and that even though pneumatic power is temperature dependent, the air temperature is conditioned by the air dryers and coolers in a compressed air system, to eliminate the condensation of water which could potentially harm the pipes and application equipment.

Therefore the temperature sensing equipment could be avoided and assuming that leaks are minimized at the terminal equipment, the pressure is assumed constant, at the line operating value of 6 [bar]. It is therefore desired that the sensing equipment is capable of sensing the flow rate at the terminal equipment. This facilitates an easier management of air energy used in manufacturing operations with a minimized equipment investment. The desired criteria for the choice of technology is related to:

- The **capability of sensing** air flow rate at a operating pressure of 6 [bar] and preferably with a flow connector fitting of 6 [mm].
- The **capability of interfacing** with a micro-controller for rapid prototyping such as Arduino, ESP, Raspberry Pi.
- The **ease of operation** as it is desired that the sensor can be easy and fast to mount at terminal equipment
- The **cost of technology** as the budget pose constraints to the purchase of sensing equipment. As the project objective is a proof-of-concept, the approximations and lower costs are rather favorable in a accuracy-cost trade-off.

The flow is defined as the amount of particles that passes through a certain point during a unit of time [28]. There are numerous technologies measuring flow rate of fluids, however only the *pilot tube* and *thermal mass flow* measurements are the most common [29].

Pilot tube and Anemometer The principle of operation of a pilot tube sensing technology is based on the insertion of the sensing unit into the duct/pipe/hose, where the fluid is to pass through. Once inserted, the pilot tube points directly into the fluid flow and measures the pressure difference between the total pressure and static pressure [28], as depicted in Figure. The pressure difference is sensed by an anemometer or other sensitive pressure gauge device and together are used to calculate the air velocity at the measurement point as depicted in Figure [30].

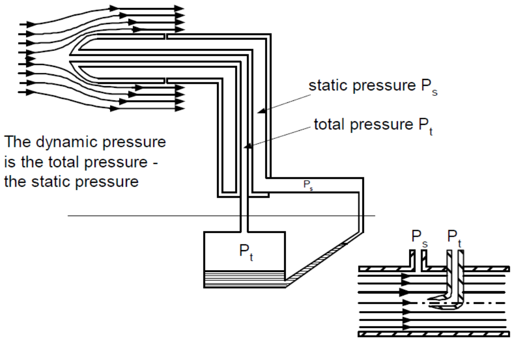


Figure 2.12: Principle of operation of pilot tube taken as excerpt from [28]

Considerations As the pilot tube is an intrusive sensing unit, other technologies are preferred to accommodate the desired criteria for ease of operation. Thus, the principle of operation of thermal mass flow technology are investigated and presented next.

Thermal mass flow The principle of operation of thermal mass flow technology is based on the measured amount of heat applied to the heating element [32]. The heating element supplies heat which is dissipated in the flowing fluid and, with increased flow velocity, more heat is lost. To compensate for the lost heat, current is increased to keep the temperature difference constant. The amount of current supplied is proportional to the mass flow [32].

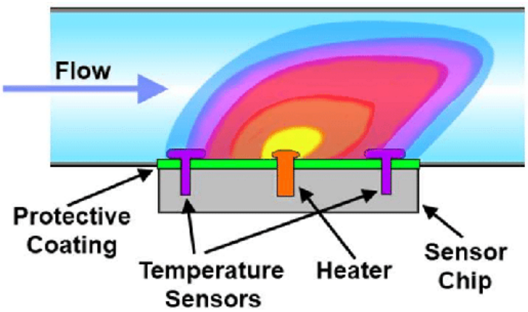


Figure 2.13: Principle of operation of a thermal mass flow taken as excerpt from [31]

Considerations The main advantage which the thermal mass flow meter has over the pilot tube technology is that the measurement is pressure-independent, thus no additional equipment is required. The measured values are therefore directly represented in volume per unit time such as $cm^3/second$ or $liter/second$ at standard conditions [29]. This makes the thermal mass flow technology a favorable choice for the project objective.

The chosen technology together with the product model is shown in Table 2.9, and the model specifications can be consulted in the product data sheets [33].

Chosen technology	Product model	Characteristics	Interfacing with microcontroller	Ease of operation	Cost of technology
Thermal mass flow sensor for gasses	SFM4100	Operating pressure range: 0-6 [bar] Output liters/min at standard conditions Flow connector fitting: 6 [mm]	Digital output (I2C)	Non-intrussive. Pressure independent. Internally lineralized and temperature compensated.	Reduced cost. No need for additional signal conditioning equipment.

Table 2.9: Chosen technology to capture the pneumatic power at the terminal equipment

2.2.5 Data collection and Acquisition

As Driscoll et al. claim in the research paper *"Industrial power and energy metering - a state-of-the-art review"*[17], there are many researchers that sought to integrate electricity consumption within operational efficiency practices, nevertheless choosing the adequate metering device presents various challenges which regard both the physical domain (meter location, number of installed meters, proximity to electromagnetic disturbances from adjacent equipment) but also challenges related to cost-performance and needed functionality. As expected, the power meter survey conducted by the above mentioned authors shows that among the needed functionality, the cost of a power meter varies with the three main instrument specifications, which in an industrial setting would define the choice of power metering technology, such as:

- **Sampling rate:** referred to as the number of samples taken per unit of time, commonly for power metering reported in samples/cycle. Devices capable of sampling high rates (up to 750 KHz) are used in highly detailed equipment behaviour investigations such as transient events (occurring at a fraction of a second). Device with lower sampling rates capabilities, provide insights into equipment minimum, average and maximum power values[17].

  As the current project scope is to collect and correlate manufacturing equipment energy consumption data and is least concerned with detecting anomalies in complex transient events, the chosen technology criteria focuses on a lower sampling rate, though high enough to capture the power electricity mains cycle in Denmark, which alternates at about 50 Hz ±1 % for 99.5 % of the year, as specified by EN 50160 standard [34].

  In signal processing, the rule of thumb for techniques of sampling is given by the famous Nyquist formula, which states that in order to avoid undersampling (inability to represent true analog continuous values as digital discrete representations), the sampling rate should be at least greater than twice the frequency of the measured system.

- **Functional requirement:** Therefore, as the power electricity mains alternate at about 50 Hz, the capability for the chosen measuring device should at least be 100 Hz sampling rate criteria.

- **Accuracy:** expressed as the ability of the device to report values close to the true value. Accuracy characteristics are classified related to the produced errors and are due to to *gain* - signal magnitude dependent (e.g. percentage of the reading, such as ±0.1%) and *offset* - independent of signal magnitude (e.g. ±1.0 millivolt (mV)).

  This aspect is related to the granularity of the measurement, such as, if the accuracy of the measured output value (e.g. micro Watts) is so small that would not produce a significant difference in the desired target (e.g. kgCO2e), the accuracy parameter would be safe to be neglected.

- **Resolution:** regarded as the change in measurement that the device can detect. In order for the analog continuous form of the measured signal (e.g. Volts or Ampere) to be processed by a microprocessor, the signal needs to be digitized (brought to a discrete/binary form). This is typically done by an ADC device (analog-to-digital converter), which has a resolution, typically expressed in bits. To determine the resolution of a device in regards with the measurand (e.g. Voltage), the digital value is computed (e.g. 2^8 = 256) and considering the microprocessor signal reference (e.g. 5 [V]) the resolution becomes $5256 = 19,53 milivolts(mV)$ per ADC count. Therefore, the smallest change detected varies with the number of bits, as computed in Table 2.10.

  Put in the context of granularity of the measurement, such as, if the resolution error of the measured output value is so small that would not produce significant differences in the desired target (e.g. kgCO2e / kWh), the trade-of of choosing a system with reasonably low resolution is considered advantageous, over a high price range.

V_ref [V]	5	5	5	5
Resolution [Bit]	8	10	12	16
Digital value	256	1024	4096	65536
V_out per ADC count [V]	19,53	4,88	1,22	0,07629

Table 2.10: Resolution of a system in terms of voltage

As the project is intended to serve as proof-of-concept, the rapid prototyping plays an important factor. Thus, a micro-controller having ADC embedded is desired. The rapid prototyping micro-controllers are available having various resolutions, ranging from 8-bit ADC to 32-bit. It was therefore decided that a ESP32-WROOM-32 having an 12-bit ADC integrated [35] would only produce an error reading of 0.0122 [V]. Thus, this would serve as foundation for the prototype solution presented in Section 4.1, presented in Concept Development chapter.

2.3 Product configurators in Enterprise ICT Systems

Literature defines a product configurator as *... software modules with logic capabilities to create, maintain, and use electronic product models that allow complete definition of all possible product options and variation combinations, with a minimum of data entries"* [36]. Several authors [37] [38], have classified the various types of product configuration systems, based on various approaches, such as:

- **Rule-based** configurator systems are which rely on a set of rules expressed in terms of conditionals with predefined sets of consequences such as *"if this then that"*. The various configurations being formulated in a forward-chaining manner such as, at each step, the system examines the set of rules until the right expression is found to be true, triggering the consequence (then clause). This type of logic can be used to carry the *domain knowledge*, components and their properties and generate information in form of automatically computing the solution related to a specific configuration [37].

- **Model-based** configurator systems, characterized by the three representation types:*logic-based, resource-based and constraint-based* approaches. [37] The *logic-based* allow complex concepts to be generated in terms of classification (introducing a new concept into the already created concepts and classify which class it belongs) and recognition (determining which class a specific concept it belongs to). The resource-based systems, employ a technical entity to be characterized by the resources it supplies, uses and consumes. The former, uses a set of properties interrelated to components and a set of connection ports to generate configurations based on the predefined constraint sets.

- **Case-based** configurator systems, which rely on reasoning about how previous solutions have previously been solved. The vital information to produce the cases, is a based on historical data (e.g. configurations of products, sold to earlier customers) [38]. This type of configurator system makes use of customer requirements to find the previous configured solutions that could accomplish those requirements.

In the AAU assembly setting, where the possible configurations of product variants are directly linked to the manufacturing resources and their capabilities to perform an operation, the rule-based configurator systems could provide the adequate environment for mapping the components and their properties to the domain knowledge of the manufacturing capability - available resources and possible routing. Therefore rule-based based on "if - then" conditional statements is chosen as an approach to develop the product configurator as proof-of-concept.

Organisations have used configuration systems in product sales for calculation of price, work out product specifications, in order processing to reduce the processing time, manufacturing specification or delivery time, but also as business strategy to increase customer satisfaction through improved dialogue with the customers [5].

As literature suggests, a favorable scenario for organisations that implement configurator systems are the principles of mass customization, for which a product is built in a module-based architecture and configuration systems are used to bind the **business/enterprise processes** to the **technical product variations** offered. For the current project, the technical product variations studied is described in Section 2.1.4.

Besides the functionality of creating technical product variations in an automated manner, product configurator systems are often integrated within enterprise systems (e.g. PLM, ERP) for management of resources (e.g. bill of materials, drawings, etc) and order processing, conducted in connection with the manufacturing capabilities (production planning and execution).

Thus, in order to formulate the functional requirements for the concept development, the following sections present the analysis of the existent ICT enterprise systems at AAU used for producing/assembling the product variants (Section 2.3.1). Additionally, the order processing (Section 2.3.2) is assumed from literature studies, as an effort to simulate an AS IS scenario at the AAU facility. Although aware of the high uncertainty and limitations imposed by generalizing case-based research, the effort aspire to provide a basis when actual order processing is existent in enterprises.

2.3.1 Analysis of Enterprise ICT systems at AAU

As the AAU assembly line is a platform used for education and testing purposes, the processes and systems involved in producing/assembling the product variants are fully automated and make use of only the Manufacturing Execution System (MES), which permits a combination of an management of resources and orchestration of manufacturing equipment via routing information.

Other enterprise systems such as Enterprise Resource Planing (ERP) are nonexistent. Furthermore the order processing is nonexistent, thus a case-study from the literature is analyzed in order to simulate the order processing at the AAU assembly line.

The assembly line operations are orchestrated by the Manufacturing Execution System (MES), which plays a similar role to an ERP (without an inventory), having stored information about the manufacturing equipment and product components. The AAU MES system allows a user to choose between already configured product variants for which the sequence of operations is hard-coded. Along with this, orders are managed in a FIFO (first in first out) manner or by planning. The MES also manages the allocated resources (process modules) for a particular order, based on work-plans. The work-plans are hard-coded relationships between the parts in the Bill of Materials and a particular resource, performing an assembly activity.

The system has been studied in order to simulate similar entities, in order to facilitate a easier integration[4] of the future product configurator. The term *Resources* encompass all equipment which interacts physically with the product and performs an assembly activity.

Each assembly activity (process), should be assigned to the correct resource, capable of executing an activity. Similar to the MES, when each assembly activity is assigned to a resource, the production work-plan is created. The topology of the assembly line is defined in the MES as a step sequence, carrying a step number, being assigned to a particular workstation IP address. Thus, the conceptualized solutions should accommodate this behaviour.

The literature [38] presents a framework including core elements which a product configurator should provide. The first element is the **database** or integration with Product Data Management (PDM) or Enterprise Resource Planning (ERP) systems, which serves the purpose of storing/retrieving the information desired to be used in the configuration process. The second element regards the **configuration logic** which defines the set of constraints related to how the product components/features can be combined.

Additionally, the **user interface** plays an important role, as this element allows a customer to navigate and make use of both the configuration logic and the database, in an visual way. Lastly, the generation of documentation (reports, quotation letters, drawings) automatizes the administrative paper work, reducing order processing activities and the costs associated with it. Thus, the development of the project takes basis in four core elements, such as:

- **Database** - developed for storing and retrieval of data related to:
  - **User registration and authentication** - User information used for accessing the system resources, storing user choices and assign configurations and orders to particular users.
  - **Product models** - Information related to product portfolio such as components, their properties and part/material identification.
  - **Manufacturing resources** - Information related to workstation IP addressing, the resources ID and program number (Op No.), operating time and energy consumption data.
  - **Business processes** - Records of order information, registration and schedule time for planned orders.
- **Configuration logic** - containing a set of rules for how the product modules (components sharing an interconnection interface) can be combined;

[4]The solution integration into the MES environment exceeds the scope of the current project, as stated in the delimitation section, however the it is desired that the product configurator would simulate the MES behaviour and entries to facilitate the ease of future integration. (i.e. work-plan operations should be assigned to the correct component)

- **User interface** - allowing the user to navigate and make use of both the configuration logic and the database, in an visual manner;
- **Automatic report generation** - the product configurator are capable of automatically generating a report or quotation letter, including a clear description of the product information (i.e. bill of materials), the estimated associated with the products within an order inquiry. For the current project scope, the quotation letter will be substituted by the equivalent carbon footprint estimation, generated by the product configured.

2.3.2 Analysis of simulated Order Processing at the AAU Assembly Line

As literature suggests [39], the important functionality of a product configurator is substituting and eliminating the routines of order processing in an enterprise. This is typically achieved by automatic data transfer (price and quotation, order and product information etc.) to the relevant entities in an enterprise (sales, production etc). Additionally, the product configuration systems are capable of automatically generating a report or quotation letter, including a clear description of the product information (i.e. bill of materials), the prices associated with the products within an order inquiry.

As explained in the previous section, the order processing is non-existent at the AAU assembly line, however a case-study from the literature is analyzed as an effort to simulate the order processing and estimate the lead time required from configuration until the order completion, formulated as AS IS scenario. Although aware of the high uncertainty and limitations imposed by generalizing case-based research, the effort aspire to provide a basis when actual order processing is existent in enterprises.

In a common scenario, a customer expresses the needs to the sales department, which in turn uses internal enterprise knowledge (e.g. available materials, capabilities to produce product features, etc.) to make a configuration of a product that satisfies the customer needs. In the literature [40] the first order processing phase is referred to as *calculation* (although generally referred to as *specification process*). As a second processing phase, if satisfied with the offer, the customer can place an *order inquiry* which needs to be managed again internally by the sales and production department, in order to ensure *a setting plan* for producing the order. As a third processing phase (*order fulfillment*), the customer places an order for which the procurement ensures the availability of parts in the configured Bill of Materials, (*shopping list*) and sends the order to production where the order is engaged into execution.

The activities involved in the order processing phases are inspired from a literature case study presented in [40], which introduces the lead time figures involved in the production of heat exchangers in an engineering and design company. Although in this research the case study is represented by a ETO (Engineer-to-Order)[5] company and the AAU assembly line is represented by ATO (Assemble-to-Order)[6], the case was the closest case study, applied to a small and medium enterprise (SME), similar to what the AAU assembly line would replicate. Therefore the engineering phase lead time accounted in the literature case study is neglected in the current study and only the order quotation activities (*calculation, setting plan* and *shopping list*) are adapted to a close estimation for the current scenario. The figures are tabulated in the Table 2.11.

Order processing phases	**Activities**	**Assumed human resourses**	**Estimated time (Man-hours)**
Specification process	Initiates discussions with the customer about product components availability and production capability. Generate the required product specifications, based on mutually agreed configuration with the customer .	1 sales representative	1
Order inquiry	Response to customer order and clarifies the solution with the customer. Checks and ensures error free specifications and formulates the setting plan, containing order entries for production .	1 sales representative	1
Order fulfillment	Response to order placement, ensures the availability of parts (BOM) for configuration and sends the order to production for execution. Prepares the relevant configuration content for the report (quotation letter) and compiles all the product and order related information.	1 sales representative	1,5
Estimated lead time			**3,5**

Table 2.11: Estimated lead time for order processing at AAU

These processes are substituted by the product configuration systems which generate the enterprise knowledge for a particular product variant chosen by the customer. The order containing technical information about the product is further sent to the production in an automated manner. In the AAU assembly factory context, this feature could be implemented by automatically sending the product, order and work-plan information to the Manufacturing Execution System (MES), responsible for executing a production order. Even though the solution integration into the current AAU assembly line enterprise system exceeds the scope of the project, it is desired that the product configuration system is conceptualized to ease the integration in the current ICT system at AAU, as previously described in Section 2.3.1.

As it is impossible to obtain accurate figures for order processing at AAU, the

[5]Engineer to Order refers to the customer co-design of product/service, followed by customized made-to-order

[6]Assemble-to-Order refers to assembling of products from standardized components

lead time figures adapted from the case-study estimation aspire to provide an AS IS scenario simulating an actual order processing existent in small and medium (SME) enterprises. As the project is formulated as a proof-of-concept, the estimated lead time figures are not feasible to be used as targets for achievement, as this would require that actual times would be recorded after having implemented the solution, in order to allow a comparison between AS IS and TO BE scenarios. The estimated lead time figures are however used to provide an insight into the financial projections, described in Chapter 5.

2.4 Analysis Summary and Reflection

The findings resulted from the analysis phases presented in the current chapter are to support the clarification of the project scope, formulate the functional requirements and facilitate the progress for the concept development. As described at the beginning of the chapter, the analysis objectives sought to provide insight into the energy consumption associated with the AAU assembly activities, investigate potential methods for quantifying the energy consumption and formulate a order processing scenario which the product configuration systems aspire to substitute.

As identified in the preliminary investigation (Section 2.1.1), the carbon emissions present at the AAU assembly line are *indirect emissions*, meaning that the carbon emissions are related to the energy consumed from the power grid, as a consequence of the sources of energy production (i.e. power stations) founded on fossil fuels and renewables [7]. As the source of production release carbon emissions into atmosphere emission factors are used in connection with the manufacturing activities to convert the energy used into equivalent mass of carbon dioxide $kgCO_2e$.

Thus, the carbon footprint embodied in a product due to the manufacturing processes energy consumption (Joules or kWh) vary to high extend across countries and regions, depending on the generation mix. During the investigation of various emission factors datasets, it was concluded that the emission factors could be queried/extracted from a country-specific updated API provided by Energi Data Service. As presented in Section 2.1.5, it is believed that this would provide more accurate an up-to-date estimation of emissions intensity characterization for the AAU assembly processes.

Collecting environmental emission data at the AAU assembly line is therefore related to both the amount of energy used and the sources of energy supply. The sources of consumption which contribute to ***indirect emissions***, are identified to be:

- **Electric energy** consumed to power the manufacturing equipment
- **Compressed air energy** consumed by the manufacturing equipment and powered by a compressor system. This energy ultimately is converted to electrical energy used by the compressed air system.

During the analysis phase presented in Section 2.1.2, the operations along with the manufacturing equipment (resources) involved in assembling the product variants were systematically categorized by their energy sources with respect to each workstation. The time required for each activity was also recorded as preliminary step to map the time distribution for each assembly process. From the analysis, the workstation points of consumption were established to be:

[7] renewables refer to clean or green energy systems such has hydro, nuclear, geothermal, solar or wind

- The station control, networking and auxiliary devices such as PLC, HMI panel
- The electric actuators for driving the conveyors
- The electric actuators of the process modules (e.g. drilling machine, robot)
- The pneumatic actuators of the process modules, the stoppers and the robot vacuuming for grippers used in pick&place operations

Thus these types of energy are considered the main contributors to formulate the partial carbon footprint of the AAU assembly processes. The analysis led to the next step, during which it was investigated how the sources of consumption could be quantified. For electric energy, the method of measurement chosen was single-phase AC current, using a fixed value of 230 Volts to approximate the power. For the compressed air energy, the air flow at the terminal equipment, assuming a constant pressure of 6 bar. However, the system losses in the pipe network and system components are accounted for, yielding a total system efficiency of 45%. This efficiency is to be used in the computation of actual power demand, at the compressor side, as elaborated in Section 2.2.3.The choice of technology capable of quantifying the types of electrical and pneumatic energy are described in Sections 2.2.2 and 2.2.4 respectively.

2.4.1 Functional Requirements specification

To facilitate the concept development phase, the functional requirements resulted from the analysis are identified to be:

- Related to sensing and data acquisition equipment

    1. Sing-phase AC current with a rate input current from 0 to 16 Ampere.
    2. Operating pressure range: 0-6 [bar]
    3. Flow connector fitting: 6 [mm]
    4. Connect to a microcontroller / microprocessor for rapid prototyping such as Arduino, ESP, Raspberry Pi
    5. Supply voltage: 3.3 or 5 V
    6. Sampling rate: min. 100 Hz sampling rate

- Related to the partial carbon footprint:

    1. **Energy consumed** - Both the electric energy and compressed air energy (with estimated system efficiency (as tabulated in Table 2.8)
    2. **Emission factor** - the carbon footprint for the the AAU assembly activities will be computed using the up-to-date and regional emission factors datasets provided by the Energi Data Service, as explained in Section 2.1.1.
    3. **Calculate and aggregate** the energy emission data (kgCO2e/kWh) for the assembly processes.

- Related to the product configurator:

  1. **Configuration logic** to characterize and compute the embodied emission data for the assembled product variants.
  2. **A database system** to enter, store or delete product related information as well as the associated manufacturing equipment and routing.
  3. **Order processing capabilities** information related to the products configured containing the bill of materials and the manufacturing equipment involved.
  4. **Authentication system** for users (organisations) to uniquely address the configurator functionality and store any data specific to user choices.
  5. **A user interface** that provides visual navigation for users to access the functionality of registration and login, configuration and order processing.
  6. **Automatic report generation** - the product configurator are capable of automatically generating a report, including a clear description of the product information (i.e. bill of materials) and the equivalent carbon footprint estimation generated by the product configured.

- Related to software for web development:

  1. **Flexibility for various screen sizes** - The capability of a page to render the interface content for different screen sizes and devices is important factor in modern web development [41]. Following the trend for web development for flexibility, the application interface components should support adaptive interface components according to the screen size to enable the user to interact with the application from any device.

CHAPTER | 3

PROBLEM FORMULATION

3.1 Problem Background and Motivation

In the quest of providing product environmental information data as a competitive-advantage strategy, product configuration systems proves a potential for connecting a customer to the available product variants and production capabilities, while automating the computation of product emission data. As AAU assembly line involves several assembly activities, the amount of energy consumed in each activity is to be quantified, converted into equivalent emission data (gCO_2e) and aggregated in order to provide environmental information for various product configurations.

As agreed with the project stakeholders, the motivation for the project is to employ technology means to characterize the energy consumption profiles of manufacturing operations involved in assembling various product variants. Along with this, partial carbon footprints (as explained in Section 1.1.3) are to be automatically generated based on product configuration. For this, the impact category of concerned is *Climate change*, as previously described in Section 1.1.3.

3.2 Problem Definition

3.2.1 Purpose and Scope

The purpose of the project is to employ technology to (1) characterize the energy consumption and equivalent partial carbon footprint of the manufacturing operations involved in assembling the AAU product variant and (2) develop a product configurator (proof-of-concept) which structures the enterprise knowledge repository and enables automatic product selection transfer from customer to manufacturing.

3.2.2 Problem Statement

As the project scope is to characterize the energy profile for manufacturing activities and develop a product configurator, it is desired to classify and address the topics of focus, which are the underlying basis for the conceptualized solutions:

1. Develop and propose a technical solution formulated as a proof-of-concept to monitor, log and quantify the energy used for the assembly processes, related to two main areas:
    - **Electric energy** consumed to power the manufacturing equipment
    - **Compressed air energy** consumed by the manufacturing equipment
2. Develop and propose a product configurator formulated as a proof-of-concept, that automates the following functions:
    - **Product configuration** based on possible product variant combinations
    - **Dynamic generation of a Bill of Materials** showing an estimation of the carbon footprint for the configured AAU product variants
    - **Dynamic generation of assembly operations** involved in the configuration containing operation time and energy consumed
    - **Order processing** containing specifications related to order execution or planning with date and time, quantity of products ordered and the total equivalent emissions for the order entry
    - **Automatic report generation** containing the assembly processes involved in the configuration, operation times and energy consumed as well as the total equivalent emissions for the order entry

The study is to be carried out on the FESTO assembly line, part of AAU production lab facility.

3.2.3 Functional Requirements

To facilitate the concept development phase, the functional requirements resulted from the analysis are identified to be:

- Related to sensing equipment
    - Sing-phase AC current with a rate input current from 0 to 16 Ampere.
    - Operating Pressure Range: 0-6 [bar]
    - Flow connector fitting: 6 [mm]
    - Connect to a microcontroller / microprocessor for rapid prototyping such as Arduino, ESP, Raspberry Pi
    - Supply voltage: 3.3 or 5 V
    - Sampling rate: min. 100 Hz sampling rate

- Related to the partial carbon footprint:

  1. **Energy consumed** - Both the electric energy and compressed air energy (with estimated system efficiency (as tabulated in table 2.8)
  2. **Emission factor** - the carbon footprint for the AAU assembly activities will be computed using the up-to-date and regional emission factors datasets provided by the Energi Data Service, as explained in Section 2.1.1.
  3. **Calculate and aggregate** the energy emission data (kgCO2e/kWh) for the assembly processes.

- Related to the product configurator:

  1. **Configuration logic** to characterize and compute the embodied emission data for the assembled product variants.
  2. **A database system** to enter, store or delete product related information as well as the associated manufacturing equipment and routing.
  3. **Order processing capabilities** information related to the products configured containing the bill of materials and the manufacturing equipment involved.
  4. **Authentication system** for users (organisations) to uniquely address the configurator functionality and store any data specific to user choices.
  5. **A user interface** that provides visual navigation for users to access the functionality of registration and login, configuration and order processing.
  6. **Automatic report generation** - the product configurator are capable of automatically generating a report, including a clear description of the product information (i.e. bill of materials) and the equivalent carbon footprint estimation generated by the product configured.

- Related to software for web development:

  1. **Flexibility for various screen sizes** - The capability of a page to render the interface content for different screen sizes and devices is important factor in modern web development [41]. Following the trend for web development for flexibility, the application interface components should support adaptive interface components according to the screen size to enable the user to interact with the application from any device.

3.3 Delimitations

There are several topics that exceed the scope of the investigation within the system to be conceptualized, such as:

- As the project scope revolves around quantifying the partial carbon footprint of a selected stage in the product life-cycle, the focus is solely oriented towards the manufacturing processes at AAU assembly line, and does not account for entire product life-cycle. However an estimation will be formulated from the relevant literature studies to formulate the embodied product life-cycle.
    – The life-cycle stages of *use* and *end of life* are excluded from the study, as these criteria are sensitive to the patterns of usage and disposal/recycling of components. Thus, no data could be collected from these stages.
- Emissions related to facility consumption (illumination, ventilation, etc.) exceed the investigation focus and are suggested as a future framework, in order to obtain a more detailed consumption profile allocated per unit produced.
- Excluded from energy audit are the workstations *T-module* (used for re-routing) and *Repair (manual) station* (used for repairs). This is because the energy consumed for the activities related to these stations are related to failures / discarded products and are therefore not part of the product configured.
- System protocols - the current study focuses on laying the foundation for the system architecture and is therefore not investigate the protocols used for communicating with other platforms, databases or industrial equipment, and would limit the investigation of the module inter-connectivity to an abstract level.
- System integration and implementation - The current scope only serves as a foundation for the concept development phase, thus both the software and sensing prototypes developed are not to be integrated within the manufacturing line environment (MES).
- Response times - As the solution is to serve as a proof-of-concept, the loading time is not a factor for development and the software solution is not to be developed for rapid response.
- Hierarchical authentication - The functionality to create hierarchical authentication roles for users exceeds the scope of the current project, nevertheless the functionality of entering data in the system by an administrator is exemplified.
- Data security - As the solution is to serve as a proof-of-concept, no measures to data security are to be developed.

Chapter | 4

Concept Development

As a response to the analysis performed and described in Chapter 2, the current chapter describes how the functional requirements and objectives are transformed into the conceptualized solution.

The concept development comprises of several objectives which the proposed solutions need to satisfy, as stated in the Problem Statement 3.2.2 and are categorized as follows:

1. Develop and propose a technical solution formulated as a proof-of-concept to monitor, log and quantify the energy used for the assembly processes, related to *electric* and *compressed air* energy, consumed to power the manufacturing equipment.
2. Develop a proof-of-concept formulated as a product configuration system, which would connect the customer to the product variants and production capabilities. The solution aspires to automate the computation of product emission data, for which the amount of energy consumed in each assembly activity is converted and aggregated to the equivalent carbon emissions ($CO_2 - eq.$).

To facilitate a clear overview of the current chapter, the following sections provide an insight into the development progress through various sections:

- Section 4.1 presents the prototypes developed to monitor, log and quantify the energy used for the assembly processes and provides insights into the empirical process as well as the contextualized energy intensity profiles.
- Section 4.2 describes the system architecture comprising three solution domains, representative for web-based client-server applications and provides insights into the each of the three-tier layers.
- Section 4.3 elaborates on the functional elements for the proposed proof-of-concept and includes descriptions of their functionality, system interfaces and back-end configuration logic.

4.1 Energy Monitoring at the AAU Assembly Line

In order to develop technical solutions formulated as a proof-of-concept to capture and quantify the energy used for the assembly processes, the following configuration was chosen:

- A split-core CT transformer (SCT-013-000) was chosen to capture the AC current clipped onto either the live or neutral wire of the equipment.
- A mass flow meter for gases (SFM4100) was chosen to capture the flow rate of compressed air at the device level, for an operating pressure of 6 [bar].
- A microprocessor ESP-WROOM-32 was chosen as a microprocessor environment to read and convert analog to digital values with an integrated 12bit ADC.

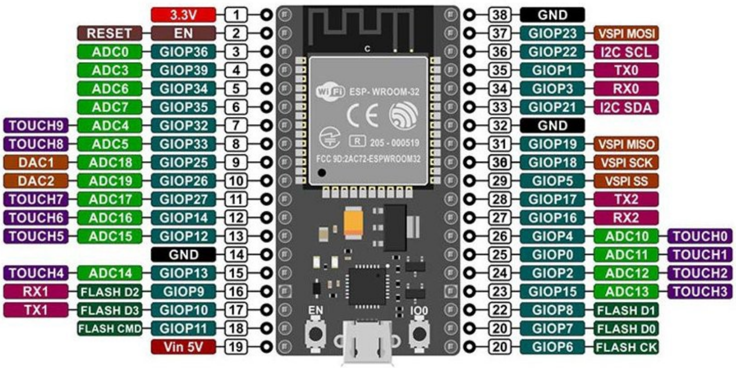


Figure 4.1: ESP-WROOM-32 microprocessor with pin configuration [42]

(a) **(b)**

Figure 4.2: **(a)** SCT-013-000 split-core CT transformer [22] **(b)** SFM4100 series digital thermal mass flow sensor for gases [33]

4.1.1 Power Metering with a CT transformer

As previously discussed in the analysis Section 2.2.2, the current measured using a current transformer, is reduced (from primary to secondary) by the number of windings (turns) in the core and the resulting secondary current is converted into a voltage by a burden resistor. The resulted voltage is measured by the analog input of the micro-controller.

Following a documented process for interfacing the CT sensor to a micro-controller, the output signal from the SCT-013-000 sensor needs to be limited to the ADC reference voltage, which is the microprocessor analog input (5 Volts). To condition the signal, the sensor output voltage is converted with the help of a burden resistor. For a range between 0 and 10 Ampere, the burden resistor required is computed and chosen to be 330 Ohm, as shown in Table 4.1.

Name	Value	Unit	Explanation
CT transformer coil	2000		Turns of winding
Max primary current RMS	10	A	Max current to be measured
Output voltage reference	5	V	Micro-controller DC Voltage
Primary peak-current	14,14	A	RMS current * sqrt(2)
Secondary peak-current	0,007071	A	Primary I peak / nr. of turns
Burden resistance	353,5	Ohm	(Output voltage/2) / Secondary peak-current
Chosen burden resistance	**330**	**Ohm**	

Table 4.1: Calculation of the burden resistor

As the voltage oscillates from positive to negative with respect to ground and the microprocessor requires a positive voltage, a voltage divider is used in form of two resistors R1 and R2, each 10 kOhm. In this way the voltage signal will always stay positive as it would oscillate above and below 2.5 V, as seen in Figure 4.3. Additionally, a capacitor of $10\mu F$ is recommended to smooth the voltage pulsation and reduce eventual noise in the circuit [43]. These values are agreed with specialized staff at AAU, in order to ensure the validity of the prototype.

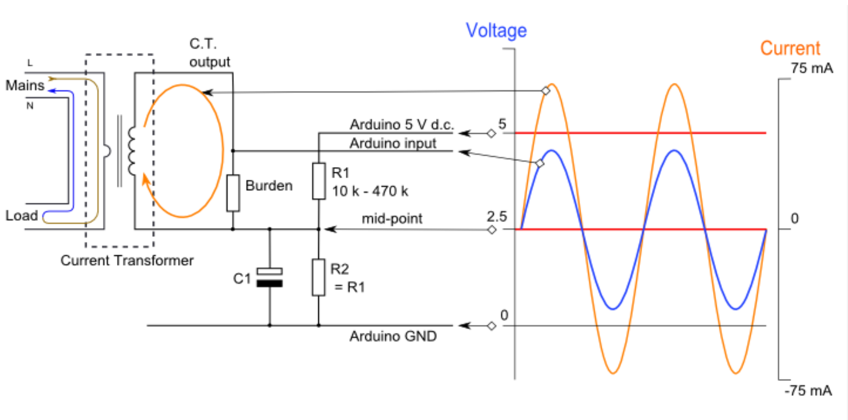


Figure 4.3: Interfacing the CT sensor with the micro-controller, taken as excerpt from [44]

In order to measure the power, the sensor is mounted on either the *line* or *neutral* wire, as seen in Figure 4.4. Thus, the alternating current flowing through the CT core, produces a magnetic field, inducing a lower current in the secondary winding, as explained in Section 2.2.2.

In a typical power measurement, both the voltage and the current is measured, although for the current objective, it was agreed with the project stakeholders that measuring current only and considering a constant voltage of 230 V, would give the desired estimation of power consumption. Therefore, as described in future framework suggestion (Section 6.1) a more accurate reading using both voltage and current readings is necessary.

Measuring the Root Mean Square (RMS) value of AC circuits would reflect the average power dissipation, equivalent in a DC circuit. The RMS current value and the approximated apparent power is computed using a library provided by emonlib on github [45], which multiplies the instantaneous current sample by itself to obtain the squares, sums the squares and divides the sum by a predefined number of samples[1], as shown in Figure 4.4.

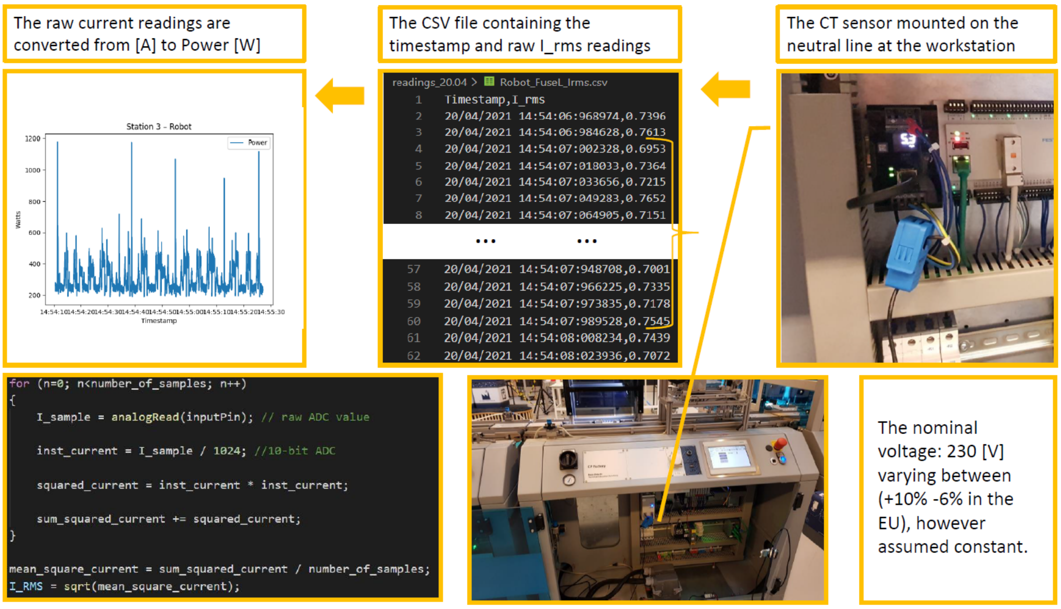


Figure 4.4: Electric Power readings at the workstation equipment

The power is computed as the product of the instantaneous voltage (V_{RMS}) by the instantaneous current measurement (I_{RMS}). As described in Section 2.2 the voltage is considered a constant value such as: 230V (+10% -6% in the EU) [16], it is possible to approximate apparent power without making a voltage measurement.

[1]As referenced in the documentation, the library script takes approx. 106 samples of current in each cycle of mains at 50 Hz, it is recommended that a good average reading is at about 14 cycles. Thus the sampling number ("number of samples") is chosen to be approx. 1480 (106 x 14).

The validity of the prototype measurements was used a global power meter which the AAU assembly line is equipped with. The global power meter provides insights into the power consumption for the entire assembly line. In order to ensure the validity of the measurements with the CT sensor setup, the global power meter is used as a point of reference to compare the CT sensor power reading match the reading with the global power meter for a known power value of the resisitve load (a bread toaster). As can be seen in Figure 4.5, the global energy meter showed 71 Watts (the workstation consumption) before turning on the resistive load and 350 Watts after the resistive load was turned on.

By subtracting the values, the resistive load power consumption is computed to be 279 Watts, matching the power value measured with the CT sensor, by an offset of 0,9 V, as shown in Table 4.2. This offset was agreed with the project stakeholders to be acceptable, keeping in mind that the project objective is a proof-of-concept, which can lay the foundation for a future framework, achieving high accuracy results. The values in the Table 4.2 were computed using measured values of the the AC voltage across the ground and micro-controller input, as well as the real Ohm value of the burden resistor.

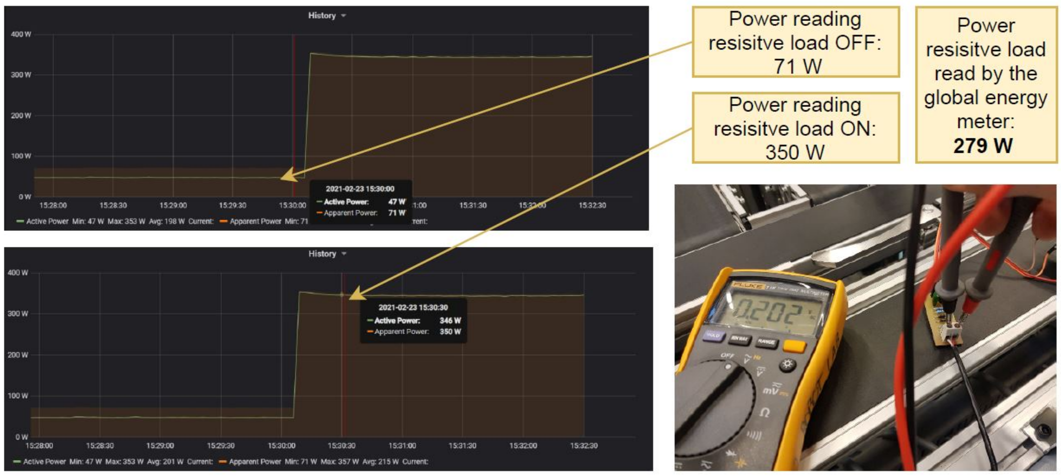


Figure 4.5: Power readings on the global energy meter check and multi-meter value

Following a reversed calculation approach, the power of the resisitve load was computed, as expressed in the table 4.2. For this, a multi-meter was used to measure the AC voltage, when the resisitve load was turned on.

4.1.2 Pneumatic Power Metering with a mass-flow sensor

As presented in the analysis (Section 2.2.4), the point of measurement necessary to characterize the power consumption for assembly activities is at the terminal equipment. As analysis showed, the amount power could be quantified by measuring the rate of air flow passing through the terminal equipment inlet, as seen in Figure 4.6. However, the power quantified at the terminal equipment does not reflect the actual power consumption at the compressor side. To obtain the actual

Measured AC Voltage	0,202	V
Measured burden resistor	328,7	Ohm
Voltage mains	230	V
Current secondary (I2)	0,0006084	A
Current primary (I1)	1,216	A
Power	**279,8**	**W**

Table 4.2: Reversed calculations for resistive load power

power consumed by the compressor, the entire system was analyzed in order to obtain the total system efficiency, as tabulated in Table 2.8. Therefore, for the power measured at the equipment, the actual power consumed at the compressor will be computed, taking into consideration the system efficiency.

The chosen sensor unit SFM4100 (as presented previously in Section 4.1), is an adequate choice as the sensor matches the terminal equipment operating pressure of 6 [bar] as the sensor operating pressure range to value up to 10 [bar] [33]. The flow connector fitting of 6 [mm] matches also the hose diameter of the equipment air inlet. The sensor can easily be embedded into a microprocessor environment, as it operates with supply voltage 5-9 VDC through an I2C interface. Following the manufacturer instructions on the sensor data-sheet the sensor unit the default I2C register address is used per gas type, in order to use the adequate calibration factor for the sensor readings. This ensures that proper fluid density is used for the sensor output.

Figure 4.6: Pneumatic Power readings at the terminal equipment

Once mounted on the line, the sensor readings were logged into a Comma Separated File (CSV), using a sampling frequency of 10 Hz. Even though the manufacturer recommends a sampling frequency of about 13 HZ [2], this was the maximum allowable frequency which the sensor was capable of reading. However, the sensor was able to successfully replicate the equipment behaviour, as also depicted in the following section in Figure 4.8.

The validity of the prototype measurements were assessed based on video recordings, investigating potential correlations between the equipment behaviour and the plotted pneumatic power graphs. Especially for the drilling machine, a strong correlation was found, which proved the validity of measurements sensitivity and sampling frequency.

4.1.3 The Energy Intensity of the AAU Assembly Line Processes

During the analysis phase presented in Section 2.1.2, the operations along with the manufacturing equipment (resources) involved in assembling the product variants were systematically categorized by their energy sources with respect to each workstation. The time required for each activity was also recorded as an effort to map the time distribution for each process. From the initial analysis, the workstation points of consumption were established to be:

- The station control, networking and auxiliary devices such as PLC, HMI panel
- The electric actuators for driving the conveyors
- The electric actuators of the process modules (e.g. drilling machine, robot)
- The pneumatic actuators of the process modules, the stoppers and the robot vacuuming for grippers used in pick&place operations

The developed prototype described in Section 4.1.2, is used to collect the amount of energy that was consumed in each assembly operation / process for each product variant. The graph shown in Figure 4.7 depicts an example of the robot instantaneous power involved in assembling the PCB and two fuses.

[2]Response time 4.6 ms @ 12-bit resolution according to the product data-sheet [33]

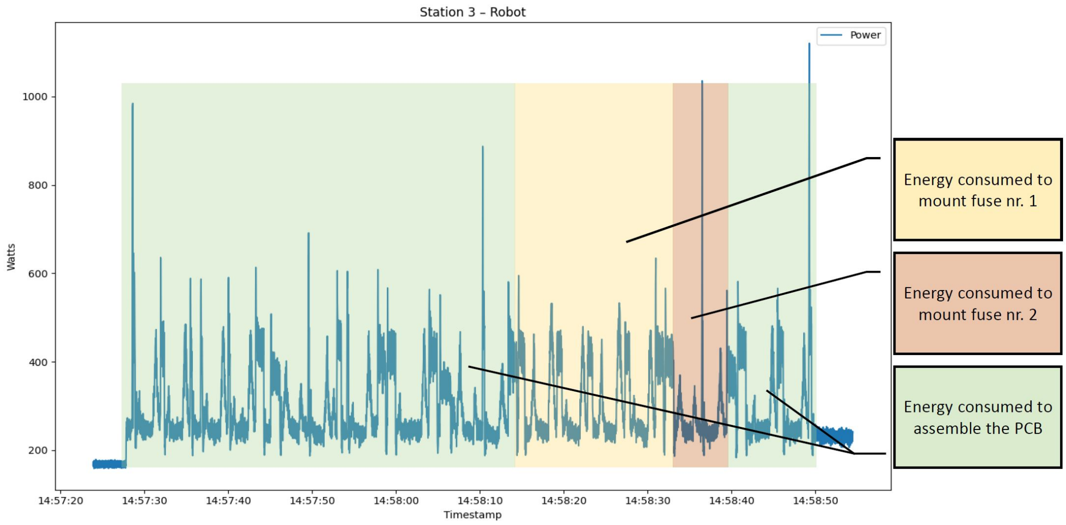


Figure 4.7: Robot power readings involved in the product components assembly

Having the timestamp (in microseconds), corresponding to each data point, a numerical integration is performed to estimate the amount of energy consumed in each operation. A similar approach was used when computing the pneumatic energy used by the manufacturing equipment. This is best explained with an example, shown in Figure 4.8, which shows the pneumatic power curve of the drilling operation at AAU.

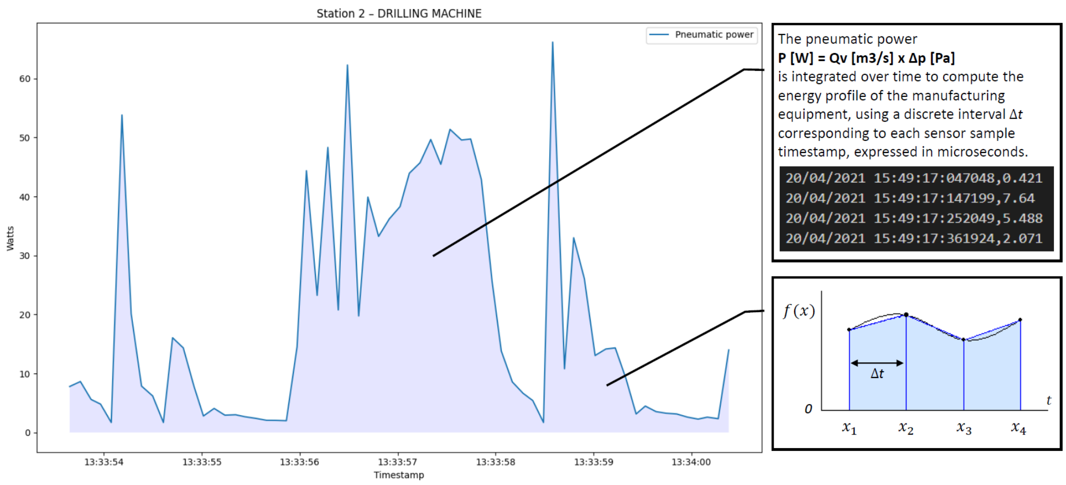


Figure 4.8: Robot power readings involved in the product components assembly

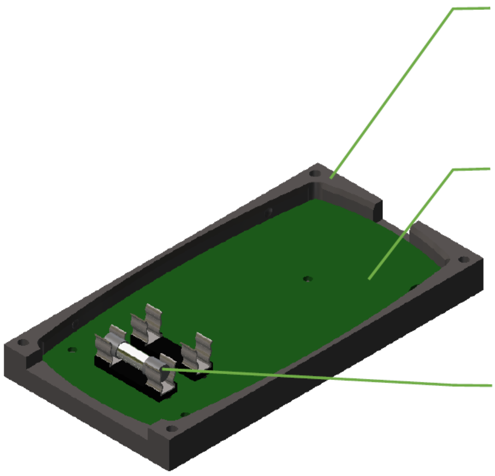
The numerical integration computes the area under the curve, using a discrete time interval (Δt), corresponding to each sample timestamp. The trapezoidal method approximates the intervals (bin density) using trapezoids instead of rectangles, thus obtaining an improved approximation [46]. The mathematical expression for discrete numerical integration over time Δt is defined in equation 4.1. Figure 4.8 facilitates a visual explanation of the process.

$$\int_a^b f(x)\,dx = \sum_{k=1}^{N} \frac{f(x_k) + f(x_{k-1})}{2} \Delta t \tag{4.1}$$

Following this approach, both the electric energy and compressed air energy consumption profiles are obtained for the manufacturing operations involved in assembling the AAU product variants. The following section gives an insight into the consumption data correlated with the product components and the manufacturing equipment involved.

4.1.4 Consumption data and Contextual Process-related information

To enable the product configurator to automatically compute and generate the equivalent partial carbon footprint for various product configurations, it is necessary to characterize the energy consumption for the manufacturing operations involved in assembling the AAU product variant and assign the energy consumption profiles to each component. Figure 4.9, presents an example of the amount of energy consumed to assemble various components.



	Operation name	Time	Electric energy [J]	Consumed power (Wh)	Pneumatic energy [J]	Consumed power (Wh)
Bottom cover assembly	IN transport	8	780,21	0,22	282,18	0,17
	Dispense bottom cover	6				
	OUT transport	3				

	Operation name	Time	Electric energy [J]	Consumed power (Wh)	Pneumatic energy [J]	Consumed power (Wh)
PCB assembly	Pick&place back cover	8	17739,30	4,93	14256,44	3,96
	Vision Orientation	9				
	Tool change for PCB	8				
	PCB pick&place	13				
	Tool change for b. cover	8				
	Pick&place b. cover	11				

	Operation name	Time	Total Electric energy [J]	Consumed power (Wh)	Pneumatic energy [J]	Consumed power (Wh)
PCB + Fuse L assembly	Pick&place b. cover	8	23513,98	6,53	23649,87	6,57
	Vision Orientation	9				
	Tool change for PCB	8				
	PCB pick&place	13				
	Tool change for fuses	8				
	Pick&place Fuse L	11				
	Tool change for b. cover	8				
	Pick&place b. cover	11				
Drill L	IN transport	8	883,70	0,25	490,93	0,14
	Drilling left	4				
	OUT transport	3				

Figure 4.9: Example consumption data representing the contextual process-related information for each component/feature

Figure 4.10 shows the energy consumption profiles for each product component, its associated assembly operation, along with the operation time. The green tables represent the power consumption due to electric energy consumption and the yellow tables show the pneumatic energy sensed at the terminal equipment and the computed value for the actual consumption at the compression side, taking in consideration the entire system efficiency (as presented in Section 2.2.3).

Thus, the consumption data represents the contextual process-related information for each component of the product variant and is used in the configuration logic of the product configurator, to automatically generate the carbon footprint of the product variants. The remaining part is to aggregate the embodied emission data, from the components life-cycle stages, until the AAU assembly line, as previously explained in Section 2.6. This operation is performed by the configuration logic presented in Section 4.3.2.

The next section provides an insight to the functionality of the product configurator, developed as a proof-of-concept based on the project requirements, as stated in Section 3.2.2.

	Operation name	Time	Electric energy [J]	Consumed power (Wh)
Bottom cover assembly	IN transport	8	780,21	0,22
	Dispense bottom cover	6		
	OUT transport	3		

	Operation name	Time	Total Pneumatic energy [J]	Consumed power (Wh)	Compressed air system efficiency	Consumed power at compressor side (Wh)
Bottom cover assembly	IN transport	8	282,18	0,08	45%	0,17
	Dispense top cover	6				
	OUT transport	3				

	Operation name	Time	Electric energy [J]	Consumed power (Wh)
PCB assembly	Pick&place back cover	8	17739,30	4,93
	Vision Orientation	9		
	Tool change for PCB	8		
	PCB pick&place	13		
	Tool change for b. cover	8		
	Pick&place b. cover	11		

	Operation name	Time	Pneumatic energy [J]	Consumed power at terminal equipment (Wh)	Compressed air system efficiency	Consumed power at compressor side (Wh)
PCB assembly	Pick&place back cover	8	6415,40	1,78	45%	3,96
	Vision Orientation	9				
	Tool change for PCB	8				
	PCB pick&place	13				
	Tool change for b. cover	8				
	Pick&place b. cover	11				

	Operation name	Time	Total Electric energy [J]	Consumed power (Wh)
PCB + Fuse L assembly	Pick&place b. cover	8	23513,98	6,53
	Vision Orientation	9		
	Tool change for PCB	8		
	PCB pick&place	13		
	Tool change for fuses	8		
	Pick&place Fuse L	11		
	Tool change for b. cover	8		
	Pick&place b. cover	11		
Drill L	IN transport	8	1001,46	0,28
	Drilling left	6		
	OUT transport	3		

	Operation name	Time	Pneumatic energy [J]	Consumed power (Wh)	Compressed air system efficiency	Consumed power at compressor side (Wh)
PCB + Fuse L assembly	Pick&place b. cover	8	10642,44	2,96	45%	6,57
	Vision Orientation	9				
	Tool change for PCB	8				
	PCB pick&place	13				
	Tool change for fuses	8				
	Pick&place Fuse L	11				
	Tool change for b. cover	8				
	Pick&place b. cover	11				
Drill L	IN transport	8	220,92	0,06		0,14
	Drilling left	6				
	OUT transport	3				

	Operation name	Time	Electric energy [J]	Consumed power (Wh)
PCB + Fuse L + Fuse R assembly	Pick&place b cover	8	25458,36	7,07
	Vision Orientation	9		
	Tool change for PCB	8		
	PCB pick&place	13		
	Tool change for fuses	8		
	Pick&place Fuse L	11		
	Pick&place Fuse R	8		
	Tool change for b. cover	8		
	Pick&place b. cover	11		
Drill L + R	IN transport	8	1272,28	0,35
	Drilling left and right	10		
	OUT transport	3		

	Operation name	Time	Pneumatic energy [J]	Consumed power (Wh)	Compressed air system efficiency	Consumed power at compressor side (Wh)
PCB + Fuse L + Fuse R assembly	Pick&place b cover	8	11856,89	3,29	45%	7,32
	Vision Orientation	9				
	Tool change for PCB	8				
	PCB pick&place	13				
	Tool change for fuses	8				
	Pick&place Fuse L	11				
	Pick&place Fuse R	8				
	Tool change for b. cover	8				
	Pick&place b. cover	11				
Drill L + R	IN transport	8	792,96	0,2202667		0,49
	Drilling left and right	10				
	OUT transport	3				

	Operation name	Time	Electric energy [J]	Consumed power (Wh)
Top cover assembly	IN transport	8	992,87	0,28
	Dispense top cover	4		
	OUT transport	3		

	Operation name	Time	Pneumatic energy [J]	Consumed power (Wh)	Compressed air system efficiency	Consumed power at compressor side (Wh)
Top cover assembly	IN transport	8	747,22	0,21	45%	0,46
	Dispense top cover	4				
	OUT transport	3				

Figure 4.10: Consumption data representing the contextual process-related information for each component/feature

4.2 Product configurator - Software Architecture

As previously described in Section 2.3, product configuration systems are information and communication technology (ICT) systems that supports the choice of product variation which can reflect customer requirements to the degree of manufacturing capabilities.

For the product configurator a web-based client-server (CS) three-tier architecture was chosen to represent the three solution domains, namely the presentation-layer, the business/domain layer and data access layer, such as:

- **The presentation-layer**: run by a web-server in a web-browser, provides the user interface for visualization and navigation of content, by combining data to a graphical interface, which supports the user to self-perform configurations of product variants. The functionality is described in details in Section 4.2.1.
- **Application/business layer**: hosted by an application server, consists of all the functional logic where the information collected in the presentation-tier (e.g. user choices or inputs) is processed using specific constraints and rules, which is the core of the rule-base configurator. This layer is also used to create, read, delete or update data in the data access tier. The functionality is developed in Python, using Flask framework.
- **The data access layer** which focuses on storing and query information from the database. The database management system chosen is SQLite, which uses Structured Query Language (SQL) and is based on a relational model. All data which the product configurator uses is stored in tables with predefined relations between the database entities. The database relational model along with a description of the entities is explained in Section 4.2.3.

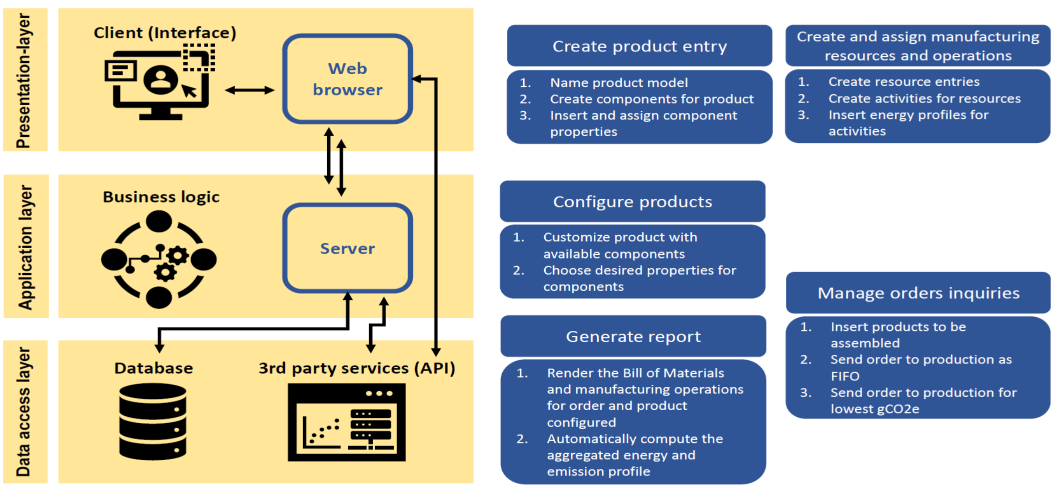


Figure 4.11: Architecture of the Product Configuration System

4.2.1 The Presentation Layer

The presentation-layer is accessible to users via web-browsers and is responsible to visually render and display the data processed by the configuration logic. The interface is developed using HTML together with CSS to statically render the user interface components, while Javasript together with JQuery are used to dynamically populate the user interface in an asynchronous manner.

The dynamic generation of data is a particularly useful feature in product configurators, as it enables the interface to have a responsive behaviour to user's actions. Moreover, the asynchronous HTTP (Ajax) request is a powerful feature to retrieve information from the server, without the need to refresh a page. Thus, the user can interact with the application in a dynamic and responsive way.

In order to reduce the repetitive HTML content on many different pages, *Jinja* is used as a tempting language for Python environment. The *'template inheritance'* that Jinja provides uses the principle of blocks to organize content. In this way, a static layout could be created and used in multiple pages as a foundation, on which the dynamic content could be rendered separately.

Data Processing and GUI Manipulation

The user interface is based on templates files which are rendered by the server, when a user access a particular route. This is exemplified in Figure 4.12, for the route */create*, which allows an admin user to create data entries which would later be displayed for a regular user as options for configuration process.

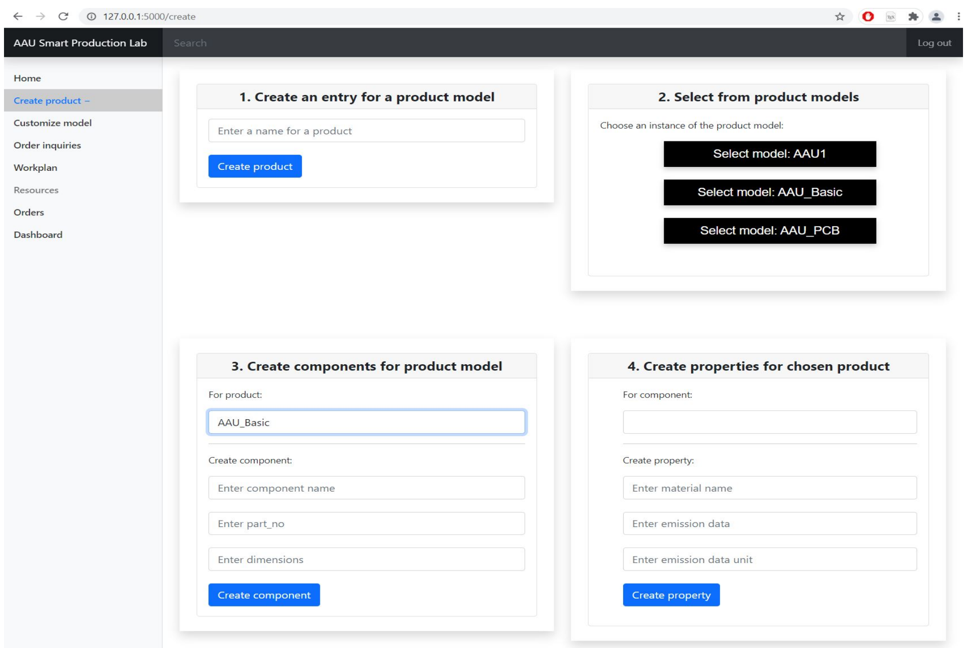


Figure 4.12: Product configurator user interface elements for "/create" route

As stated in the project delimitation (Section 3.3, the functionality to create hierarchical authentication roles exceeds the scope of the current project, nevertheless the functionality of entering data in the system by an administrator is exemplified. The Figure 4.12 represents the layout of the application interface consisting of *vertical navigation bar* which enables a user to navigate through the application resources, and a *horizontal navigation bar* which points the user to a log out route, for signing-off.

The interface components enumerated from 1 to 4 are card containers [3]. The first card allows a user to create an entry in the database for a new product model, by inserting a product name in the input field and submitting it to the server.

Having stored a new product model entry, a user can create entries for its components, by first selecting the product model from container 2 and afterwards selecting a relevant product in the drop-down selection field, which appears in the card container 3. When selecting the product model, the user will be redirected to a product specific route, using dynamic routing.

As a last step, to create a property entry for a specific component, the user can select the desired component for which the property data can be stored. After this point, the components and properties created could be used in the configuration process, which is explained in Section 4.3.2.

4.2.2 Application and Business layer

The middle layer of the application is responsible for the logic of the product configurator. As the user interacts with the interface from a particular route, it generates specific requests to the server which are processed by the server logic corresponding to the route where the user sent the request from. In the current application, the inner logic combines three elements: the users actions from the presentation-layer, the data records retrieval from the database and data retrieval via an external API. Being the core of the product configuration system, the functionality is detailed in the configuration logic Section 4.3.2 and order processing Section 4.3.3.

4.2.3 The Data Access layer

The database developed serves the storage and retrieval of data used for the configuration logic in the Application/business layer and visualisation in the presentation-layer. The records of data are stored in tables being accesses by an Object Relational Mapper (ORM), called SQLAlchemy, which is a Python SQL toolkit that provides all the features and flexibility of an SQL and additionally, Object-Oriented Programming (OOP) capabilities. OOP enables the generation of data-access classes, called *models*, which represent the tables in the database with a functionality of

[3] interface component developed using Bootsrap CSS framework

Python classes, methods, and objects become the tools for interacting with SQL databases.

Taking basis in the project requirements as stated in Section 3.2.2, the data required for the product configurator is split into tables, each storing relevant information, such as:

- **Related to order processing**:
  - **Users** table store information necessary for authentication having elements/columns such as name, username and password and an ID as an unique identifier. Users are related to *orders* table, such that for each user, several orders could be related.
  - **Orders** table store data relevant to processing orders. The data records contain a *start* and *end timestamp entry*, a *quantity entry* which stores how many products an order could contain as well as the total $CO2 - eq$. for executing the order and registered emission factor for the order.The *foreign key* allows the *users* to establish a child connection constrain to the parent table *orders*. Additionally, the orders table establishes a relation to *products* tables, such that for each order, numerous product(configurations) could be stored and processed.
- **Related to the Bill Of Materials**:
  - **Products** table stores product related information containing an entry for the configured product and two foreign keys to child connection constrain to both parents - the *users* and *orders* tables. This is done in order to ease the configuration logic and enable data retrieval based on a user id or an order id respectively. Moreover, the products table establishes a relation to *components* tables, such that for each product, various product components could be retrieved.
  - **Components** table allows data records such as *name*, *part number* and *dimensions* of a component to be stored and establish a child connection constrain with parent *products* tables and a relationship with the child *properties* tables, such that for each component, there are numerous properties which a user can choose.
  - **Properties** table enables the application to make use of components property-related data (product features) and store data records such as *material name*, *emission data values and units*. The properties have child-connection constraint to the parent table *components*.
- **Related to the manufacturing equipment and routing**:
  - **Workstations** table contain records related to information routing of the manufacturing equipment containing *workstation name*, *the topology step number* necessary for correlating the operations work-plan for a particular order in a sequential manner and stations *IP addresses* enabling

data transfer between the Manufacturing Execution System (MES) and stations PLC. Additionally, the workstations table establishes a one-to-many relation to *resources* table, such that for each workstation, multiple resources could be assigned to.

- **Resources** table represent the digital asset of the manufacturing resource which performs an operation for each product feature. The records contain the resource *name* and the *resource ID* which is used by the workstation PLC to transfer logic instructions to the resource actuators, which ultimately perform an activity (routine) on the product/part. Thus, the resources table have a one-to-many relationship to the *activities* table, such that for each resource, several activities (routines) could be performed.
- **Activities** table stores consumption related data *electric energy, pneumatic energy* and the *program number* required for the PLC to initiate the control logic for the resource actuators, associated with the product property (feature). Every activity has a one-to-one relation to the *properties* table, such that for each activity performed, there is an associated product component feature (property).

To facilitate an overview over the relations in the database, Figure 4.13 shows the entity relation diagram.

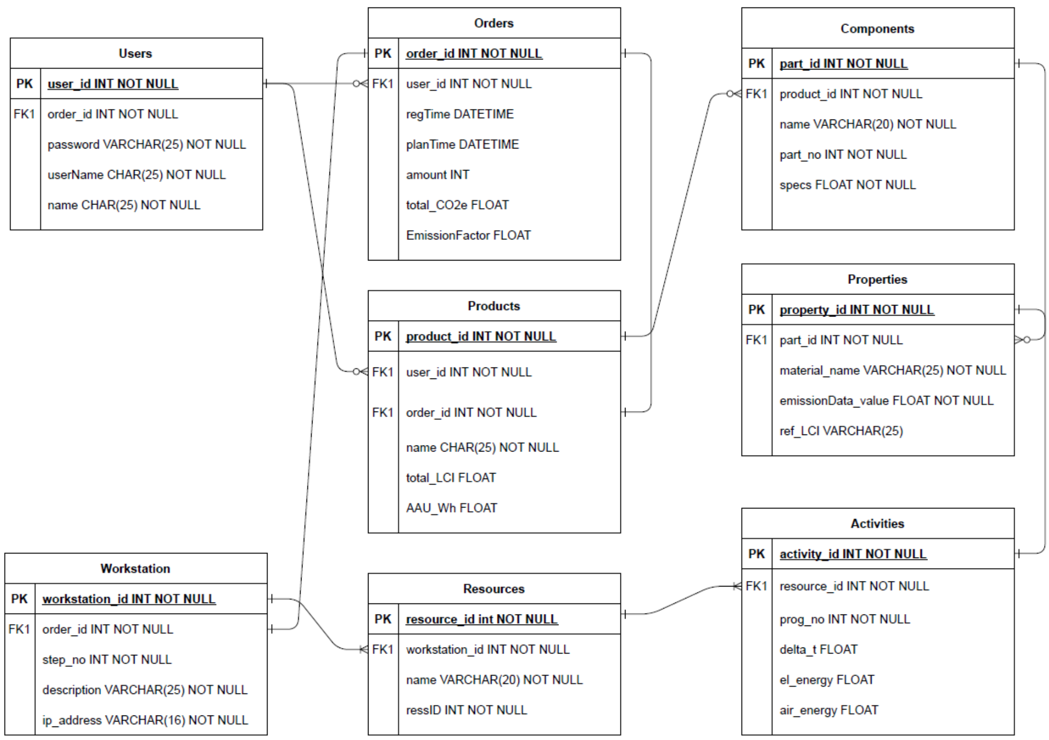


Figure 4.13: Entity-relationship diagram of the database relational model

4.3 Product configurator Functional Components

4.3.1 User Registration and Authentication

The registration process plays an important role in any ICT system as it provides the means to gather information about the users which interact with the system. Having stored the user information, the users actions can be related to the users unique identification.

Authentication is the process of verifying the identity of an user, and acts as a barrier to unregistered users to interact with the product configurator. A unique identifier is associated with a user which is the username or user id. The actions which the registration and authentication system comprises are:

1. The user registers using an identifier like username or email and uses a password to unlock access to the system;
2. The application stores user credentials in the database encrypting the password;
3. Post successful registration, the user enters credentials for logging in;
4. On successful authentication, the user is allowed access to specific resources;

4.3.2 Model customization - Configuration logic

When a user interacts with the product configurator interface, the system is capable of processing a particular product configuration defined by the users actions.

As explained in Section 2.3, the configurator merges the technical information of a product represented as Bill of Materials (BOM) with the capabilities of manufacturing operations associated with these.

The developed proof-of-concept makes use of both the server side (application layer) and the client-side (presentation-layer) to realize the configuration logic. In this request-response cycle, the following steps take place:

Step 1 - Initialization Starting by accessing the URL route responsible for staring the configuration process, the client sends a Hypertext Transfer Protocol (HTTP) GET request to the web server route which in turn sends a response with the information (hypermedia document) to be displayed. In this step, the user can choose between three options. The first option, is to self-configure a product variant or the second option to choose between two pre-configured models including a product variant associated with the least carbon footprint and a product variant associated with the most.

- 1.1 - If a user chooses a predefined product variant, the user is redirected to order processing page, where the user could complete the order inquiry process.
- 1.2 - If a user chooses to configure the product model, the user is requested to enter a name for the desired model and proceeds to the next configuration step by submitting the model name.

The server receives the user input sent by the client as a POST request and stores in the database the product information for a particular user. The process ends with with redirecting the user to a dynamically generated URL route which renders the page for the next configuration stage, namely customization.

Step 2 - Customization Configuration process starts with the user choices upon which components the product should contain. For this, the interface prompts the user the available choices of components, part of the product variants, as described by the Product Variant Master (PVM) in section 2.1.4. As the components interfaces carry various constraints, this is reflected in the software, which uses logic conditional statements to constrain the user choices (e.g. the user cannot include a fuse for the configuration, if the PCB component is not chosen). This logic is implemented on the client side, using Javascript as represented in the Swim Lane diagram 4.14.

From the user's perspective, the product configurator displays information about the product components and their properties, providing a configuration sandbox, which the user can use to make the desired configuration choices. Taking basis in the trend for web development for flexibility (as specified in functional requirements Section 2.4.1 and in problem statement 3.2.2), the interface components adapts according to the screen size, and follow the responsiveness requirement as shown in Figure 4.15.

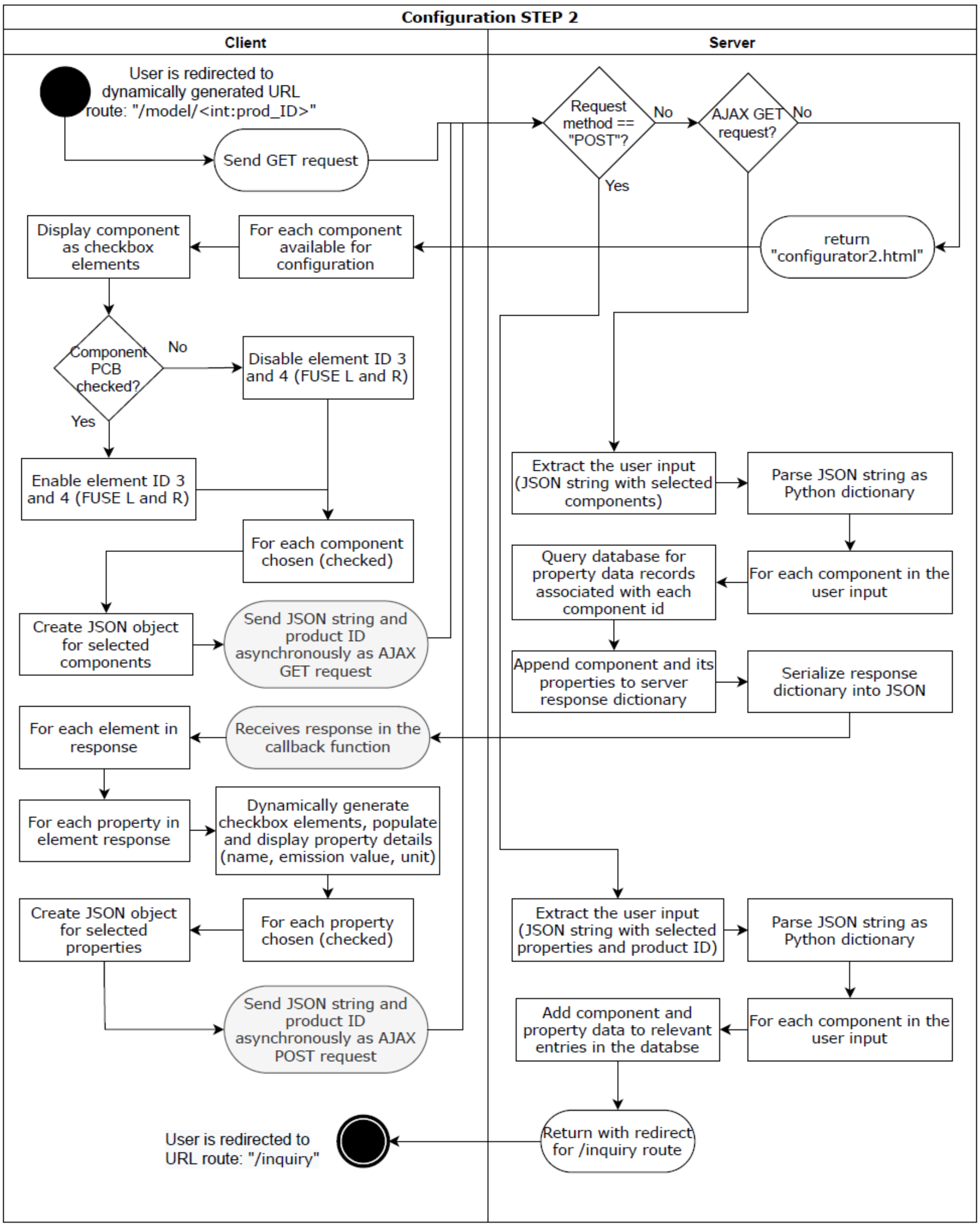


Figure 4.14: Swim lane diagram showing the configuration logic

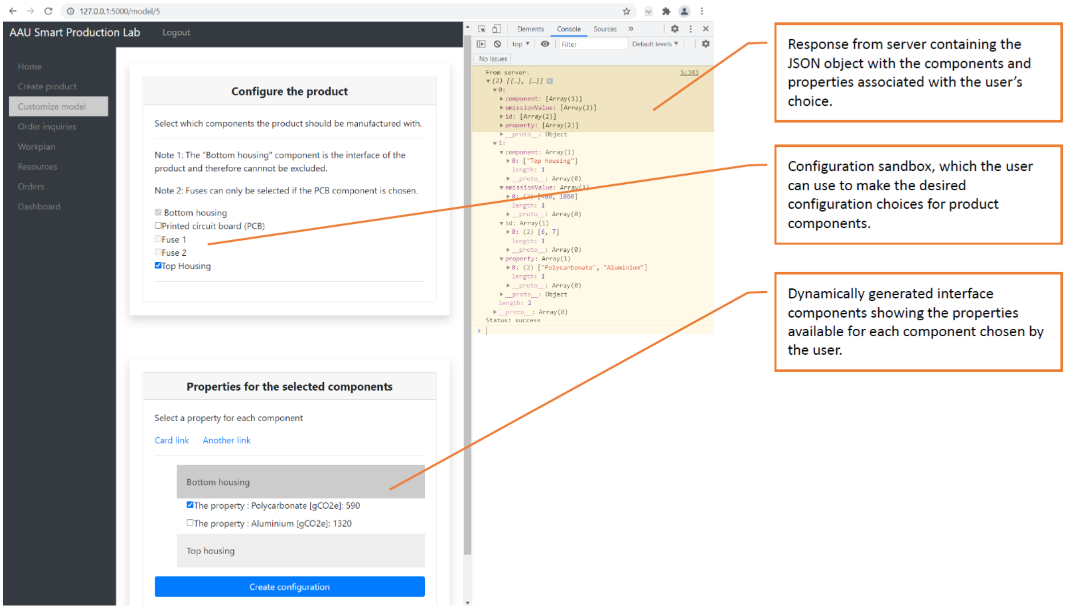


Figure 4.15: Product configurator interface showing product customization step 2

4.3.3 Order Processing

As described in Section 2.3, product configurators are ICT enterprise systems which enables a level of automation for the order processing by combining the technical product information (e.g. BOM) with the manufacturing capabilities. This section will present the solution developed based on the functional requirements formulated in Section 2.4.1 and shows the steps which the current proof-of-concept manages an order, including the generation of Bill of Materials, quotation of equivalent kgCO2 for a particular product configuration and the manufacturing operations and equipment involved in the product variant assembly.

As described in the analysis (Section 2.3.2), the order inquiry process and the final quotation as well as the production planning are typically substituted by the product configurator which generates the the enterprise knowledge for a particular product configuration chosen by the customer. Also, the order is sent to the production in an automated manner.

Thus, the order processing is reflected in the software solution in three steps, and are presented as a continuation of the processes which a user undergoes when interacting with the application.

Step 3 - Order inquiry The application leads the user further to the order inquiry, a step in which the user is prompted with all the product models configured during step 1 and 2. The data rendered as table entries, represents an overview over the product models configured by the user and comprises the product variant information such as name, Bill of Materials (BOM) related to each product variant and the carbon footprint estimation for the Bill of Materials. The desired product variants can be sent to production, once the quantity desired for producing each model is inserted (i.e. how many pieces to produce for a particular model).

As presented in Section 2.1.1, the Energi Data Service, provides APIs which contain datasets as (nearly) updated history for the CO2 emission factors due to electricity consumed in Denmark (g/KWh). As an additional service, a 8-hours prognosis is made available with a resolution data of 5 minutes, updated every 15 minutes [13].

The up-to-date emission factor from the API is prompted on the interface by directly fetching data on the client side, using Javascript and SQL statements. In this way simplifying and reducing the response time from the request-response cycle by directly querying the API as opposed to having the internal server to query the API, processing the data and sending it as a response to the client. Figure 4.16 facilitates the understanding of this functionality, showing the asynchronous HTTP (Ajax) request.

Figure 4.16: Querying the Energi Data Service for updated emission factor for converting the electric energy into equipvalent mass (gCO_2e)

As a novelty application feature, the user can opt for sending the order to production as FIFO (first in first out) or as planned order. Sending an order to production as a planned order, the application makes use of the 8-hours forecast and searches for the lowest emission factor value.

Equivalently, sending an order to production as FIFO, would compute the equivalent carbon emissions (gCO_2e) calculated using the up-to-date emission factor for the time-interval during which the assembly would takes place. [4] This value is registered and used to generate the emissions profile for the specific order.

[4] As the solution is formulated as a proof-of-concept, this feature is simulated in the application using the emission factors at the moment of order completion only in the application environment and not in the actual production instance.

Considering the advantages of a product configurator which directly interacts with the customer, this option represents an innovative way to enable a user/customer to aiming for the lowest/minimum emission value used in assembling the product variant, ultimately achieving a lower emission profile. Figure 4.17 depicts the interface of the application responsible for the order inquiry process.

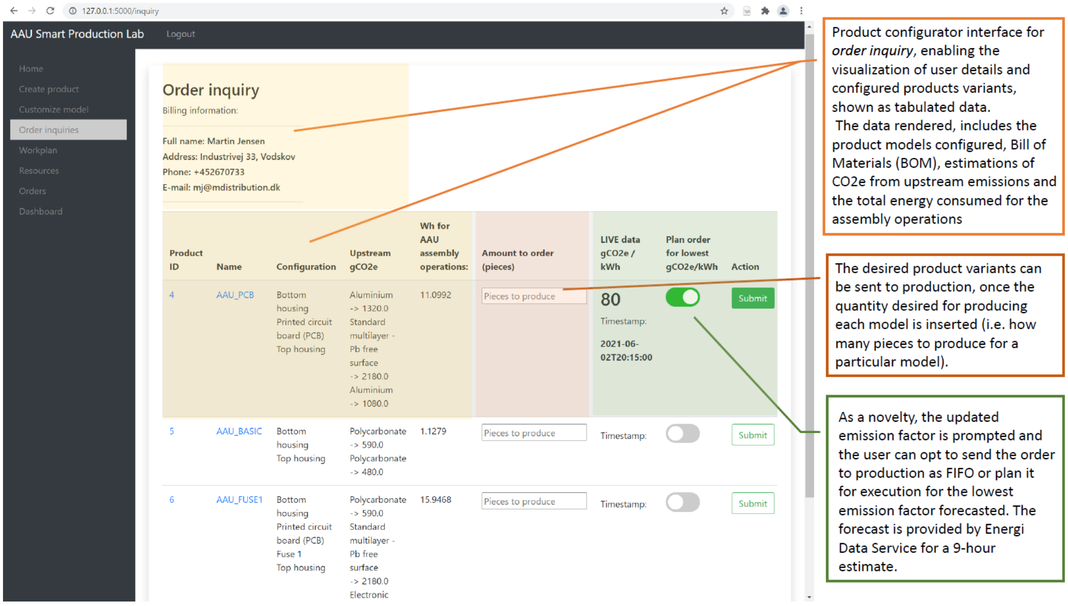


Figure 4.17: The Graphical User Interface showing the order inquiry as a first step in the order processing

Once the user decides upon the how many product models to order and whether to send the order to production as planned for lowest carbon emission factor [5], the order details are stored as entries in the database. As explained in Section 4.2.3, the system simulates the MES environment at AAU assembly line and stores records for orders with a time stamp and the equivalent emission factor for a assembling a particular configuration. Next, the user reaches to the fourth step of the product configurator, namely the *Order completion*, which is presented in the following section.

Step 4 - Order completion Once the customer has decided upon the quantity of product models to order and whether to send the order as FIFO or planned for the minimum environmental impact, the application redirects the user to the fourth configuration step where status information about all the orders is prompted. In this step, all the order information is compiled. As seen in Figure 4.18, the user can consult the orders overview which contains elements related to the configuration, the registration and scheduled timestamp for the order, as well as information related to pieces ordered (quantity) and the emission factor used.

[5] Based on the forecast provided by the Energi Data Service [47]

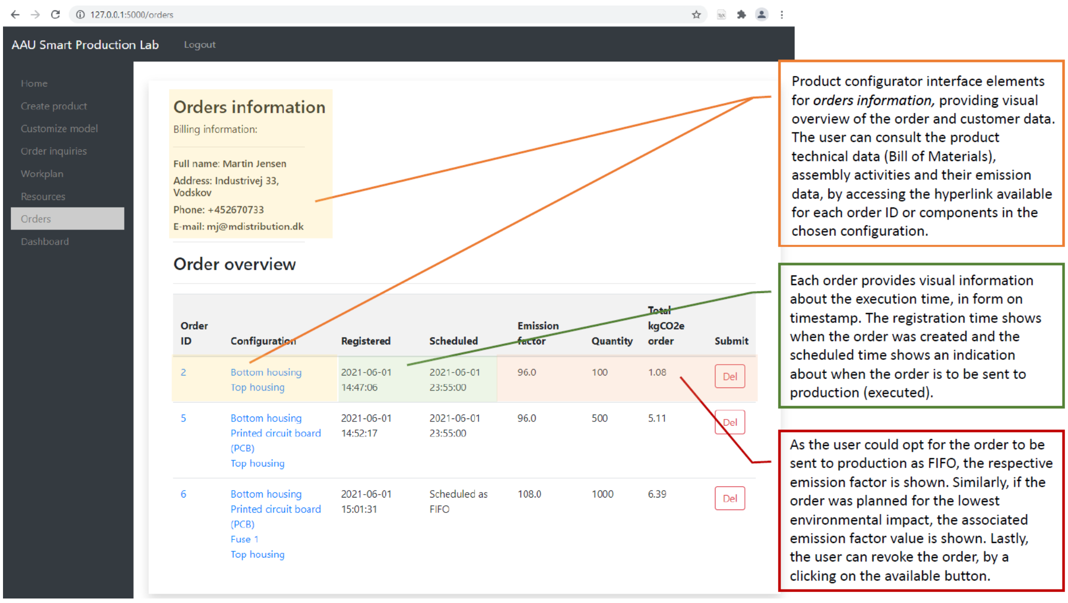


Figure 4.18: The *Order overview* enabling a visual representation of the processed orders

As shown in Figure 4.18 the user can consult details about a specific order via hyperlinks. The hyperlinks redirects the user to dynamically created routes which gathers and generates all the information about an order. This leads to the last step *Report generation*, a functionality presented in the next step.

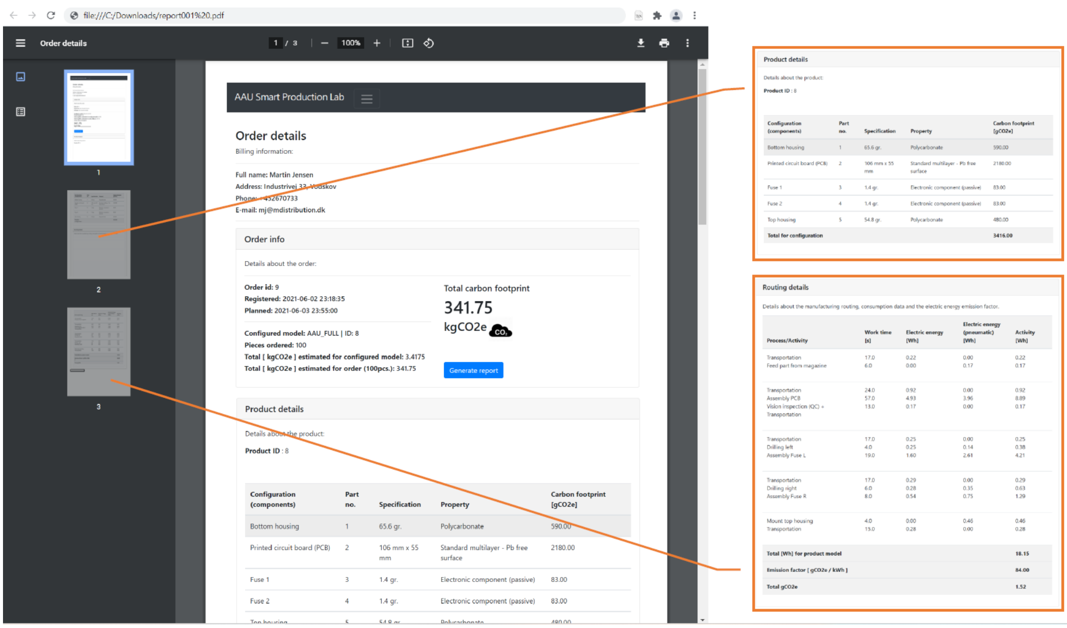


Figure 4.19: The automatically generated report containing order details, Bill of Materials and manufacturing activities with estimations of equivalent carbon emissions

Step 5 - Report generation Once the user access a hyperlink for a particular order, the user is redirected to the *Order details* route. The *Order details* represents the last step of the order processing, which enables the user to consult detailed information about the order containing product technical data such as the Bill of Materials, manufacturing operations and the associated emission data, as presented in Figure 4.19. If the user requests a report, all the above mentioned information is rendered in a portable document format (PDF) format.

4.3.4 Points of Achievement

The product configuration system described in the previous sections accomplishes all the functional requirements proposed in Sections 3.2.2 2.4.1. The solution formulated can successfully substitute the administrative and manual routines, typically existent in order processing phases from *Specification*, *Order inquiry* to *Order fulfillment*, tabulated in table 2.11 and detailed in the case-study Section 2.3.2. The accomplished targets are are summarized below:

Order processing phases	**Activities**	**Achieved by the proposed product configuration system**	**Achieved**	**Saved processing time**
Specification process	Initiates discussions with the customer about product components availability and production capability. Generate the required product specifications, based on mutually agreed configuration with the customer	1. Enables customers to authenticate and self-customize the available combination of components and choose the desired properties for components in an intuitive and user-friendly interface. 2. Automatically stores the customer preferences for the product variants customized, under each user profile.	Yes	1
Order inquiry	Response to customer order and clarifies the solution with the customer. Checks and ensures error free specifications and formulates the setting plan, containing order entries for production	1. Automatically compiles the user choices from the specification process in an error-free manner. 2. Stores the compiled product variant data for each order entry in the Order inquiry route. 3. The user can send the order to production as planned or FIFO automatically.	Yes	1
Order fulfillment	Response to order placement, ensures the availability of parts (BOM) for configuration and sends the order to production for execution. Prepares the relevant configuration content for the report (quotation letter) and compiles all the product and order related information.	1. Automatically computes the aggregated energy and Co2e emissions related to product information and production capabilities. 2. Automatically render a report containing the product Bill of Materials with manufacturing activities and the estimated carbon emissions.	Yes	1,5
Estimated lead time reduction				**3,5**

Table 4.3: Product configuration system achievements for lead time reduction in order processing at AAU

Chapter 5

Financial Considerations

The proposed product configurator solution formulated as a proof-of-concept is intended to provide a basis for a more complete ICT ecosystem at the AAU assembly facility. As described in Section 2.3 product configurator systems (PCS) are enterprise supportive software which provide value in form of management of knowledge about product technical details, equipment and the business (administrative, quotation) manufacturing (routing, timing) processes involved. The primarily value which could be monetized is the automation of the administrative and manual routines involved in *order processing* phases as described in the simulated case-study in Section 2.3.2 and points of achievements in Section 4.3.4. As literature suggests [40], the product configuration systems substitutes these routines and the lead times and cost implications correlated with them.

As the AAU assembly line is used as a platform for technical education, there order processing phases is non-existent. However it is desired to elaborate the monetary gains and investment costs related to implementation and integration of product configuration systems in enterprises. To achieve this, the financial assessment takes basis in the lead time reduction tabulated in table 2.11, which presents an estimation scenario for the order processing at AAU, formulated and adapted based on the closest case-study found literature [40].

Although aware of the high uncertainty and limitations imposed by generalizing case-based research, the current chapter presents relevant financial assessment metrics and aspire to provide a basis when actual order processing is existent in enterprises. Therefore the financial assessment takes an underlying basis in the formulated case-study for order processing in Section 2.3.2.

The focus of the current chapter is oriented solely towards the lead time reduction in order processing, which implicitly reduces the resources in an enterprise and thus affects the cost associated with it. To assess whether the project is economically feasible, a cost-benefit analysis is conducted and presented in the following sections.

5.1 Return on Investment for Product Configuration Systems

The initial step in quantifying the value of ICT systems is to conduct a return on investment (ROI) of the project. According to [48], ROI is a cost-benefit tool to estimate a ratio of profitability of projects by estimating the traditional ROI elements. For the current project, the ROI elements are:

- Project costs - the related investment costs of development, deployment and maintenance
- Tangible benefits - monetary benefits gained by having the solution implemented

This ROI analysis is performed in order to determine whether the project is advantageous of pursuit and is typically computed as the ration between the net profit and the investment costs [49]:

$$ROI = \frac{Total \quad financial \quad gains - Cost \quad of \quad investment}{Cost \quad of \quad investment} \tag{5.1}$$

It is shown in numerous literature studies how product configuration systems contribute to reduction in human resources, the related man-hours for administration of business processes and lead time for order processing [50], [51], [52] and [53]. The review of literature brought into light that product configuration systems influences the value creation differently in project phases typically substituted (quotation, engineering, production) and have therefore different return on investments. The differences are a consequence of the reduced costs for manhours (i.e. in sales, engineering departments) which the automated solution aspires to reduce. The next section introduces the estimate of costs accounted for in the financial assessment.

5.1.1 Estimate of Costs

The costs discussed in literature [40] which was used to adopt the the AAU ordering process case study (Section 2.3.2, computes the costs associated with a generic product configuration system for which purchase of software and annual licenses are necessary.

In the current case, the solution developed is a customized solution which does not imply the payment of any software purchase or annual license fees, although the research and development hours[1] used for modelling and programming the conceptualized solution are instead computed. These are part of the Capital Expenditure and are tabulated in table 5.1.

Estimated costs elements associated with PCS	**Amount**	**Unit**
Research & Development		
Weekly workload	40	hours
Project span	20	weeks
Engineering hourly wage	256,87	DKK / hour
Total estimated costs	**205.500,00**	**DKK**
System configuration		
Power and Energy Logger ACMEL Model PEL 103	10.919,32	DKK
Gauge pressure sensor SDE5-D10-FP-Q6E-P-M8	699,68	DKK
Temperature sensor	1500,00	DKK
Total estimated costs	**14524,95**	**DKK**
Total estimated capital expenditure (CAPEX)	**220.024,95**	**DKK**

Table 5.1: Estimated expenditure associated with the development of PCS

In addition to the System configuration and R&D costs, the "hidden" costs related to deployment phase, which include testing and system integration are neglected in the current assessment, as to obtain those, a comprehensive planning to collect and achieve accurate figures is required to be conducted in close collaboration with the system integrators. However the maintenance costs are assumed as operational expenditure and tabulated in table 5.2.

Estimated operational costs elements associated with PCS	**Amount**	**Unit**
Monthly workload	15	hours
Target period	3	years
Engineering hourly wage	256,87	DKK / hour
Yearly maintenance costs	**15.412,50**	**DKK / year**
Total estimated operational expenditure (OPEX)	**15.412,50**	**DKK / year**

Table 5.2: Estimated operational costs elements associated with PCS

[1]The engineering hourly wage is computed based on [54] for 40 hours weekly workload and an average salary of 41.100,00 DKK monthly

5.1.2 Estimate of Financial Benefits for Target Period

A target period between 3 to 5 years represent a commonly used ROI period for assessing financial projections. For the current financial assessment a target period of 3 years is chosen as this would reflect a conservative estimate, avoiding the risks implied in an eventual over-estimation. The target period acts also as a time constraint for which the investment costs are desired to be returned.

Considered solely from a monetary perspective, the financial benefits represents the saved cost of paid working hours involved in the configuration and order processing, as elaborated in Section 2.3.2, Table 2.11. A cost which a company may have to cover if the automated configuration and order process is not implemented.

The estimated benefits included in the assessment are shown in Table 5.3 and reflect the yearly savings for having substituted the workload of a full-time sales representative[2] focusing on the three order processing phases, before having implemented the solution:

Estimated benefits elements associated with PCS	**Amount**	**Unit**
Estimated saved time per order	6,5	hours
Weekly workload	40	hours
Number of orders for weekly workload	6	orders / week
Sales hourly wage	162,50	DKK / hour
Yearly savings	**13.650,00**	**DKK**
Total benefits for target period	**491.400,00**	**DKK**

Table 5.3: Estimated benefits elements associated with PCS

[2]The sales hourly wage is computed based on [55] for 40 hours weekly workload and an average salary of 26.000,00 DKK monthly

5.1.3 Estimated ROI and Payback

As previously documented, the return on investment presents the financial gains of the proposed project, compared to its relative cost. For the current project the investment value ROI% shows that the expected net benefits are more than double in relation to the expected costs. Table 5.4 shows the total costs of the project which includes the capital expenditure (CAPEX) as initial investment and the operational expenditure (OPEX). The initial investment (CAPEX) consist of the development costs and costs of sensing equipment proposed as system configuration in Table 5.1. The operational costs (OPEX) comprise the estimated maintenance yearly costs such as maintenance of product data and software, as tabulated in Table 5.2.

For a target period of 3 years, ROI is computed using the cumulative net benefits of 225.137,55 kr. divided by the cumulative total costs 266.262,45 kr. As it can be seen in Table 5.4, for the estimated cash flow, the net benefits are more than double than the investment and operational costs, yielding a ROI of 85 %, which proves the project worth of pursuing, with the condition that the assumed expenses for system configuration will not be altered and the order cost associated with man-hours are within estimations. If the reduction of lead-time for order processing is higher, the project is confidently worth of pursuing.

	Initial	Year 1	Year 2	Year 3	Cumulative total	Unit
Total costs	220.024,95	15.412,50	15.412,50	15.412,50	266.262,45	DKK
Total benefits	0	163.800,00	163.800,00	163.800,00	491.400,00	DKK
Net benefits	-220.024,95	148.387,50	148.387,50	148.387,50	225.137,55	DKK
Estimated return on investment (ROI)					**85**	%

Table 5.4: Estimated ROI associated with PCS

Once the ROI yields a satisfactory ratio, the time frame needed for the investments to be covered is computed as payback period. The payback period starts once the initial investment starts the project and ends when the cumulative benefits exceed the cumulative costs. For the current project, the payback period rounds 1,63 or approximately 20 months. This shows that the benefits will occur in the second year of the desired target period of return.

	Initial	Year 1	Year 2	Year 3	Unit
Cumulative Costs	220.024,95	235.437,45	250.849,95	266.262,45	DKK
Cumulative Benefits	0	163.800,00	327.600,00	491.400,00	DKK
Estimated payback period				**1.63**	months

Table 5.5: Estimated payback period associated with PCS

Based on above mentioned assumptions, the cumulative costs and benefits are plotted in Figure 5.1, which facilitates the visual representation of the break-even point and computed payback period of approximately 20 months.

Figure 5.1: Break-even point for financial projection

5.1.4 The Net Present Value (NPV)

Since monetary investments are typically loans which have an interest rate attached over the time, it is expected that the future values of benefits are greater than present values of investment. To complete the financial assessment, the Net Present Value (NPV) is used to evaluate the costs and benefits over time in order to account for the time value of money.

The time value accounts for the fact that money invested could earn interest elsewhere, also known as the opportunity cost. The time value of money uses a *discount rate*, which is a a company-specific figure to account for the fact that money could earn interest rate pursuing alternative projects, typically known as an opportunity cost.

Set initially to the cost of capital, to adjust the cost and benefit cash flows over time, in today's value, the discount rate is typically adjusted from the company's cost of capital rate to account for the project risk, using the suggest formula from [48]:

$$NPV = I_0 + \frac{I_1}{1+r} + \frac{I_2}{(1+r)^2} + ... + \frac{I_n}{(1+r)^n} \tag{5.2}$$

where I_0, represents the net benefits for year zero, I_1 for the first year and so on. The exponent n represents the step number of years for the target period, and r the discount rate, held constant through the computation.

As mentioned previously, the discount rate is a subjective figure for each enterprise which may be computed containing internal financial metrics such as weighted average cost of capital (WACC), which regards companies market equity and debt, corporate tax rate, depreciation and more [56].
To estimate a discount rate, a figure is chosen to reflect the interest rate of a bank loan required for the capital investment (up-front cost). Money which a company may have to cover throughout time. As banks internally compute this value based on the amount borrowed and several metrics including inflation the an estimation of the market value of the company, a discount rate of 7% is assumed, based on various bank interest rates for enterprise loans [57].

	Net benefits	**Present Value**	**Unit**
Initial	-220.024,95	-220.024,95	DKK
Year 1	288.787,50	138.679,91	DKK
Year 2	288.787,50	129.607,39	DKK
Year 3	288.787,50	121.128,40	DKK
NPV		**169.390,75**	**DKK**

Table 5.6: Estimated Net Present Value associated with PCS

Since the Net Present Value of the estimated project cash flow is positive, the initial investment is covered, thus pursuing the project is financially viable. However the limitations of the current NPV analysis is that it requires many assumptions, however it aspires to provide a know-how for conducting financial assessments for product configuration systems.

Chapter 6

Conclusion and Future Development

In a market where consumer behaviour is shifting to become sustainable-oriented, environmental regulations become more stringent and taxation on carbon emissions continue to rise, the sustainable manufacturing paradigm is gaining more and more attention. In this new context, providing environmental information becomes both a competitive-advantage strategy which enterprises can tap into.

Nowadays technological advancements and the availability of information on the world-wide-web enable the information about the products and their production to be compiled into product configuration systems (PCS), which connect the consumer to the production capabilities. For the customers this represents an advantage, as PCS allows the user to have an impact on the product configuration, enabling an active choice over components, their related production schedule and order acquisition. Moreover, for the enterprises, product configuration systems aspires to substitute and eliminate the administrative routines involved in order processing (and the costs associated with) by automatic data transfer between the customer and production.

In addition to the above mentioned benefits, the motivation of gathering carbon emission data inventories for products and making the data available in web-based ICT systems, would support the emission data transmission across the value chain, contributing to a more accurate and transparent environmental product data. Therefore, the project objectives regard two focus areas such as:

1. Employ technology means to characterize the associated carbon emissions profiles of manufacturing operations involved in producing/assembling various product variants at AAU assembly line.
2. Develop a proof-of-concept formulated as a product configuration system, which would connect the customer to the product variants and production capabilities. The solution aspires to automate the computation of product emission data, for which the amount of energy consumed in each assembly activity is converted and aggregated to the equivalent carbon emissions.

To achieve the objectives, the AAU assembly line activities associated with assembling the various product variants was analyzed as an initial analysis phase, in order to identify the contributing sources of CO_2 and systematically structure the assembly activities, their operation time along with the related equipment. As presented in Section 2.1.2, the contributing sources of carbon emissions proved to be solely *indirect emissions*, as a consequence of the energy consumed for each assembly activity. Thus, collecting environmental emission data at AAU assembly line is therefore related to both the amount of energy used and the sources of energy supply.

The characterisation of carbon emission profiles could be done by quantifying, collecting and aggregating the energy intensity for the *electrical energy* consumed to power the manufacturing equipment and *compressed air energy* consumed by the pneumatic equipment but powered and distributed by the compressor system.

As analysis has shown, quantifying only single phase AC current and considering a constant voltage of 230 [V] would produce the desired estimation for power consumption. Similarly, the quantification of the pneumatic power consumed implied the measurement of air flow at the terminal equipment, considering the 6 [bar] operating pressure of the AAU assembly line constant. However, as the compressed air is supplied by a compressor system which distributes the air through a complex network of pipes, the transmission losses are compiled into the total system efficiency, η_{tot} = 45%, as tabulated in table 2.8. This reflects a realistic scenario, for which the pneumatic power consumed at the compressor side is computed, to serve as actual energy intensity, for relevant assembly activities.

Once the methods of measurements were investigated (presented in Sections 2.2.1 and 2.2.3 respectively), the analysis led to the technology assessment step (presented in Sections 2.2.2 and 2.2.4, for which various technological means were considered. The split-core current transformer (CT) sensor and thermal mass flow sensor were deemed preferable for attaining the desired choice criteria. These technologies form the basis for the empirical study and were used to quantify the energy consumption, as presented in section 4.1 as part of the concept development phase.

In order to conceptualize the proof-of-concept for the product configurator system, the existent ICT enterprise systems at AAU were analyzed and presented in Section 2.3 to establish which ICT system elements are necessary to accommodate in the conceptualized solutions. A framework for core elements was established comprising a **databse**, used for storing and retrieving technical product manufacturing data, **configuration logic** which defines the set of rules for configurations and a **user interface** enabling the visual navigation for performing the configuration.

Once the energy profiles were associated with each component assembly (Figure

4.9, the amount of energy used was reflected in the sequence of assemblies. This showed that the PCB and first fuse implies higher energy consumption because of the sequential routines performed by the robot, such as change of grippers and pick-and-place operations. These routines account for higher CO2 emissions, even though they represent non-value adding activities.

Additionally, the order processing analysis (Section 2.3.2) was carried out to simulate an AS IS scenario at AAU facility for which the order processing lead time was assumed to round 3,5 hours, based on literature studies and adapted to AAU assembly context. Although aware of the high uncertainty and limitations imposed by generalizing case-based research, the effort aspire to provide a basis when actual order processing is existent in enterprises.

The concept development phase, brought into light that developing product configuration systems are a complex task, as many components are to be developed and inter-linked. However once developed, the ease and rapidity to configure a product, make an order inquiry and send the order to production truly denotes the system value. The system aspires to automate the above mentioned manual routines by automatic management of order and automatic generation of reports, containing the total aggregated emission data for a specific product configured. The data comprise both the embodied emissions estimated for the product components life-cycle and the indirect emissions resulted from the AAU assembly activities.

The conceptualized solutions presented in Sections 4.2 and 4.3 reflect the analysis findings and compiles the functional requirements into a client-server (CS) three-tier architecture. This architecture was found most suitable to support the initially formulated motivation of making the product emission data available in web-based ICT systems. The availability on the web, enables customers to log-in as users, and self-configure the components for a product variant.

As it can be seen in the automatically generated report (Figure 4.19, the carbon emission associated with the AAU assembly activities represents a small part of the entire carbon footprint embodied in the product. This is an expected evaluation, as the indirect emissions accounted in an assembly context represents only a small share, compared to the entire product life-cycle which a product undergoes (as described in Figure 1.1). Moreover the energy consumption of manufacturing equipment at AAU is significantly lower than all the pre-processing and processing activities involved in the life-cycle of the product from the raw material extraction, pre-processing and post-processing, as estimated in Section 2.1.4.

The review of literature brought into light that product configuration systems influences the value creation differently in project phases typically substituted in *Engineer-to-Order* (ETO) enterprises where products components are developed based on customer requirements or *Assemble-to-Order* (ATO) where products have standardized components, already available as standard or off-the-shelf. These two paradigms imply different product configuration processes and have therefore different return on investments. The differences are a consequence of the reduced costs for man-hours (i.e. in engineering departments or in sales) which the automated solution aspires to reduce.

An innovative functionality Having the information available and the power to decide over which components and properties carry the highest CO2-equivalent emissions, the user can opt for choosing the configuration with the lowest impact. Once the configuration is chosen, the user is again empowered to have an active choice on the order environmental impact, as presented in Section 4.3.3. This is achieved by the functionality to send the order to production as First In First Out (FIFO) or plan the order for a time interval when the carbon emissions are lowest for a KWh.

The availability of the embodied emissions for a product, supports the data transmission across the value chain and potentially contributes to a more accurate and transparent environmental product data. Having transparent product emission data, creates a competitive-advantage strategy for enterprises, in a increasing sustainability-oriented market.

Moreover, as environmental information becomes available to the consumer, and consumers are empowered to make an active choice on the purchase, it is believed that enterprises would continuously strive to develop products having least environmental impacts. This could potentially lead to CO2 reductions in the atmosphere, as an advantage for the environment and a clear benefit for humanity.

6.1 Suggestion and Future Framework Considerations

Related to order processing

- Sending the order either as FIFO or scheduled for the lowest emission factor (as explained in section 4.3.3), would require a scheduling algorithm for planning. Once integrated into the MES, the algorithm should query the MES database for existing orders and plan according to a queuing system, such that eventual double planning or misplacement of orders are avoided.

Related to system integration

- As the current project was formulated as proof-concept, the system integration into the AAU enterprise ICT system (MES) would be favorable to complete the interconnection between the customer and the manufacturing capabilities. The software system and the proposed database, facilitates the integration of necessary IP addresses, the PLC program number for executing specific routines for each resource ID, however the system should be accommodated or adjusted to the Manufacturing Execution System environment and its database.

Related to energy sensing

- As presented in the analysis (Section 2.2.2 and 2.2.4, to obtain accurate energy profiles would require employing both electrical energy meters capable of sensing current and voltage as well as a more advanced compressed air meter, sensing the fluid temperature, pressure and flow.

Related to upstream emission data

- Formulated strictly for show-case purposes, the emissions data estimated for each component (presented in Section 2.1.4) are estimated based on life-cycle inventories (LCI) datasets, available on ecoinvent 3 database. The estimations are formulated to reflect that components material matter and have different environmental impacts. In a real scenario, LCA consultants are preferred to model the life-cycle of various components used in the product variant.

Related to financial assessment

- The formulated financial assessment aspire to provide a foundation for evaluating whether the system development is financially worth of pursuing. However the assessment is based on estimated reduction lead time of order processing. As emphasized, in the relevant chapter, more accurate figures could be obtained for scenarios where order processing, the lead time reduction and its associated costs are existent and actually measured. The proposed system configuration provides also an uncertainty factor, thus a re-assessment is required if the system configuration would be changed.

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Appendix | A

Product related carbon footprint

A.1 The Global Warming Potential values

The elements (components) suggested to be included in the data management plan can be seen on the next page, as a direct excerpt from Greenhouse Gas Protocol [58]:

Global Warming Potential Values

The following table includes the 100-year time horizon global warming potentials (GWP) relative to CO_2. This table is adapted from the IPCC Fifth Assessment Report, 2014 (AR5)[i]. The AR5 values are the most recent, but the second assessment report (1995) and fourth assessment report (2007) values are also listed because they are sometimes used for inventory and reporting purposes. For more information, please see the IPCC website (www.ipcc.ch). The use of the latest (AR5) values is recommended. Please note that the GWP values provided here from the AR5 for non-CO_2 gases do not include climate-carbon feedbacks.

Global warming potential (GWP) values relative to CO_2

Industrial designation or common name	Chemical formula	GWP values for 100-year time horizon		
		Second Assessment Report (SAR)	Fourth Assessment Report (AR4)	Fifth Assessment Report (AR5)
Carbon dioxide	CO_2	1	1	1
Methane	CH_4	21	25	28
Nitrous oxide	N_2O	310	298	265
Substances controlled by the Montreal Protocol				
CFC-11	CCl_3F	3,800	4,750	4,660
CFC-12	CCl_2F_2	8,100	10,900	10,200
CFC-13	$CClF_3$		14,400	13,900
CFC-113	CCl_2FCClF_2	4,800	6,130	5,820
CFC-114	$CClF_2CClF_2$		10,000	8,590
CFC-115	$CClF_2CF_3$		7,370	7,670
Halon-1301	$CBrF_3$	5,400	7,140	6,290
Halon-1211	$CBrClF_2$		1,890	1,750
Halon-2402	$CBrF_2CBrF_2$		1,640	1,470
Carbon tetrachloride	CCl_4	1,400	1,400	1,730
Methyl bromide	CH_3Br		5	2
Methyl chloroform	CH_3CCl_3	100	146	160

Industrial designation or common name	Chemical formula	GWP values for 100-year time horizon		
		Second assessment report (SAR)	Fourth Assessment Report (AR4)	Fifth Assessment Report (AR5)
HCFC-21	$CHCl_2F$			148
HCFC-22	$CHCLF_2$	1,500	1,810	1,760
HCFC-123	$CHCl_2CF_3$	90	77	79
HCFC-124	$CHClFCF_3$	470	609	527
HCFC-141b	CH_3CCl_2F	600	725	782
HCFC-142b	CH_3CClF_2	1,800	2,310	1,980
HCFC-225ca	$CHCl_2CF_2CF_3$		122	127
HCFC-225cb	$CHClFCF_2CClF_2$		595	525
Hydrofluorocarbons (HFCs)				
HFC-23	CHF_3	11,700	14,800	12,400
HFC-32	CH_2F_2	650	675	677
HFC-41	CH_3F_2	150		116
HFC-125	CHF_2CF_3	2,800	3,500	3,170
HFC-134	CHF_2CHF_2	1000		1,120
HFC-134a	CH_2FCF_3	1,300	1,430	1,300
HFC-143	CH_2FCHF_2	300		328
HFC-143a	CH_3CF_3	3,800	4,470	4,800
HFC-152	CH_2FCH_2F			16
HFC-152a	CH_3CHF_2	140	124	138
HFC-161	CH_3CH_2F			4
HFC-227ea	CF_3CHFCF_3	2,900	3,220	3,350
HFC-236cb	$CH_2FCF_2CF_3$			1,210
HFC-236ea	CHF_2CHFCF_3			1,330
HFC-236fa	$CF_3CH_2CF_3$	6,300	9,810	8,060
HFC-245ca	$CH_2FCF_2CHF_2$	560		716
HFC-245fa	CHF2CH2CF3		1,030	858
HFC-365mfc	CH3CF2CH2CF3		794	804
HFC-43-10mee	CF3CHFCHFCF2CF3	1,300	1,640	1,650

Industrial designation or common name	Chemical formula	GWP values for 100-year time horizon		
		Second assessment report (SAR)	Fourth Assessment Report (AR4)	Fifth Assessment Report (AR5)
Perfluorinated compounds				
Sulfur hexafluoride	SF_6	23,900	22,800	23,500
Nitrogen trifluoride	NF_3		17,200	16,100
PFC-14	CF_4	6,500	7,390	6,630
PFC-116	C_2F_6	9,200	12,200	11,100
PFC-218	C_3F_8	7,000	8,830	8,900
PFC-318	$c\text{-}C_4F_8$	8,700	10,300	9,540
PFC-31-10	C_4F_{10}	7,000	8,860	9,200
PFC-41-12	C_5F_{12}	7,500	9,160	8,550
PFC-51-14	C_6F_{14}	7,400	9,300	7,910
PCF-91-18	$C_{10}F_{18}$		>7,500	7,190
Trifluoromethyl sulfur pentafluoride	SF_5CF_3		17,700	17,400
Perfluorocyclopropane	$c\text{-}C_3F_6$			9,200
Fluorinated ethers				
HFE-125	CHF_2OCF_3		14,900	12,400
HFE-134	CHF_2OCHF_2		6,320	5,560
HFE-143a	CH_3OCF_3		756	523
HCFE-235da2	$CHF_2OCHClCF_3$		350	491
HFE-245cb2	$CH_3OCF_2CF_3$		708	654
HFE-245fa2	$CHF_2OCH_2CF_3$		659	812
HFE-347mcc3	CH3OCF2CF2CF3		575	530
HFE-347pcf2	CHF2CF2OCH2CF3		580	889
HFE-356pcc3	CH3OCF2CF2CHF2		110	413
HFE-449sl (HFE-7100)	C4F9OCH3		297	421
HFE-569sf2 (HFE-7200)	C4F9OC2H5		59	57
HFE-43-10pccc124 (H-Galden 1040x)	$CHF_2OCF_2OC_2F_4OCHF_2$		1,870	2,820
HFE-236ca12 (HG-10)	CHF2OCF2OCHF2		2,800	5,350

Industrial designation or common name	Chemical formula	GWP values for 100-year time horizon		
		Second assessment report (SAR)	Fourth Assessment Report (AR4)	Fifth Assessment Report (AR5)
HFE-338pcc13 (HG-01)	$CHF_2OCF_2CF_2OCHF_2$		1,500	2,910
HFE-227ea	$CF_3CHFOCF_3$			6,450
HFE-236ea2	$CHF_2OCHFCF_3$			1,790
HFE-236fa	$CF_3CH_2OCF_3$			979
HFE-245fa1	$CHF_2CH_2OCF_3$			828
HFE 263fb2	$CF_3CH_2OCH_3$			1
HFE-329mcc2	$CHF_2CF_2OCF_2CF_3$			3,070
HFE-338mcf2	$CF_3CH_2OCF_2CF_3$			929
HFE-347mcf2	$CHF_2CH_2OCF_2CF_3$			854
HFE-356mec3	$CH_3OCF_2CHFCF_3$			387
HFE-356pcf2	$CHF_2CH_2OCF_2CHF_2$			719
HFE-356pcf3	$CHF_2OCH_2CF_2CHF_2$			446
HFE 365mcf3	$CF_3CF_2CH_2OCH_3$			<1
HFE-374pc2	$CHF_2CF_2OCH_2CH_3$			627
Perfluoropolyethers				
PFPMIE	$CF_3OCF(CF_3)CF_2OCF_2OCF_3$		10,300	9,710
Hydrocarbons and other compounds - direct effects				
Chloroform	$CHCl_3$	4		16
Methylene chloride	CH_2Cl_2	9	8.7	9
Methyl chloride	CH_3Cl		13	12
Halon-1201	$CHBrF_2$			376

IPCC data sources for more information:

- AR4 values: https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html
- AR5 values: https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf (p. 73-79)

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