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Methodology for Carbon Emissions Neutrality in Industrial Manufacturing

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Greenhouse gas emissions reduction in the industrial sector focusses on energy-intensive industries (EIIs) since they comprise a significant proportion of industrial sector emissions. However, collective emissions from non-EII industries is substantial and organisations require guidance to reach carbon neutrality. This study addresses the research question 'What methodologies and modelling tools do industrial organisations use to plan and subsequently achieve carbon emissions neutrality?' There is a research gap between general, independent, emissions abatement measures and organisation-specific plans developed using in-house or commercial software and/or energy management consultants. This study proposes a detailed, open access, cross-sectoral and strategic methodology aimed at the organisational level. A Supplier-Input-Process-Output-Customer (SIPOC) methodology is used in an adapted Define-Measure-Analyse-Improve-Control (DMAIC) framework to provide a high-level, visual pathway to carbon neutrality, clearly indicating the supplier, input, process, output, and customer for each carbon mitigation step. The Analyse step involves an energy audit, and heat and renewable energy studies to generate modelling tool input. The Improve step models the potential emissions abatement measures in priority order of efficiency, new technology, heat recovery, and renewables, with the budget or timeline as the dominant parameter. The model outputs are a carbon neutrality waterfall as the pathway, and a sensitivity graph to highlight influential modelling inputs. Future work includes modelling tool development, and validation with a case study of a medical device manufacturing facility.

1. Introduction

More than 40 % of Europe's greenhouse gas (GHG) emissions are attributed to the energy and manufacturing sectors (Vieira et al., 2021). Energy-intensive industries (EII) contribute approximately 64 % of the EU's industrial emissions (de Bruyn et al., 2020). The European Green Deal highlights the importance of reducing EII emissions as EIIs supply intermediate products to numerous other industries, forming part of their supply chains. They are vital to the European economy, (Vieira et al., 2021) and have been the focus of industrial emission reduction. However, GHG emissions of non-EIIs remain an important part of the industrial sector as the collective savings may be considerable. The emissions attributed to the industrial sector as a whole should be addressed from a societal and corporate social responsibility perspective. This work considers the research question: 'What methodologies and modelling tools do industrial organisations use to achieve carbon neutrality?' A hybrid methodology of Define-Measure-Analyse-Improve-Control (DMAIC) and Supplier-Input-Process-Output-Customer (SIPOC) for carbon neutrality is proposed for industrial organisations. The remainder of the paper is as follows: Section 2 provides background and identifies the research gap; Section 3 presents the proposed methodology and introduces the model; Section 4 concludes the paper and details the future work.

2. Background

2.1 Existing emissions abatement approaches

At the organisation level, broad, independent emissions-reduction measures (e.g. efficient lighting, electric vehicles) are well known, and typically not presented within structured pathways to carbon neutrality. The British Standards Institution (BSI) (2014) is the only globally recognised independent certification standard for carbon neutrality (EcoAct, 2022). With its accompanying methodologies, it provides a framework with which to calculate,

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report, and verify GHG emissions; certify an entity as carbon emissions neutral; and set future emissions targets. The International Organisation for Standardization (ISO) 50001 (2018) is an energy management standard that provides a framework to manage and monitor energy consumption, with the organisation determining how to demonstrate energy reduction. Although these standards and accompanying methodologies are important for reducing emissions of organisations, a review thereof indicates that none provide a technical, industry-focused, step-by-step approach to carbon neutrality. Gerres et al. (2019) reviewed 40 EII decarbonisation pathways and roadmaps of various countries and associations. They noted differing approaches, with a focus on top-down strategies not specific to industry sectors—such as the German Federal Environmental Agency’s proposal to use renewable methane as syngas. They further noted that these pathways typically lack the detailed technology required for the proposed strategies. The pathways of sector associations represent bottom-up approaches, focussing on measures specific to sector processes, with no cross-sectoral applicability. For instance, The European Cement Association’s 2050 roadmap focusses on measures to reduce GHG emissions of each of its five processes (CEMBUREAU, 2020); however, these are presented as individual steps for each process rather than a step-by-step pathway to carbon emissions neutrality. Wei et al. (2022) developed a carbon emissions neutrality roadmap and MILP optimisation model for industrial parks, based on energy, economic, and environmental analyses. However, they found the generalisation of the optimal model to be limited in case studies, and recommend a weighting system for cost and emissions to optimise the solution. Sinai Technologies appears to have the most advanced commercial software platform for emissions abatement. It claims to be ‘the planet’s leading decarbonisation platform’ (SINAI Technologies, n.d.), which is supported by the 2021 award of World Economic Forum technology pioneer (Yoon and Hillyer, 2021). This is proprietary software that could not be examined in detail, and the following analysis is based on the information presented on the website. The Sinai Technologies platform comprises a tool set for calculating Scope 1, 2, and 3 GHG inventories; value chain management; baseline forecasting; mitigation scenario modelling of abatement potential and financial effects, with a selection of carbon offset projects; and internal carbon pricing. The indicated software output for mitigation is a marginal abatement cost curve, from which appropriate abatement measures are selected. This, combined with the user-defined carbon targets, is used to determine the carbon cost and price. The software does not appear to generate a pathway to carbon neutrality, and the solutions are subject to the typical shortcomings of abatement curves, namely the lack of consideration of the interactions between abatement options, the temporal dynamics, uncertainty, and additional benefits (Kesicki and Strachan, 2011). Alternatively, organisations may employ private consulting to develop detailed carbon management plans and carbon neutrality roadmaps.

2.2 Research gap

Collaboration with an industrial partner indicated that an appropriate methodology and associated model for organisations should be open-access, operate at the organisational level, be applicable across different sectors, model various scenarios, be strategic in forming a roadmap, and be highly detailed. None of the existing tools and methodologies discussed in Section 2.1 meet all six criteria, clearly indicating a research gap (Table 1).

Table 1: Illustration of research gap

Tool/Methodology	Open access	Organisation level	Cross-sectoral	Scenario modelling	Strategic	Highly detailed
Standards & methodologies	Mix of ✓ and ✗	✓	✓	✗	✗	✗
Independent measures Top-down strategies	✓	✓	✓	✗	✗	✗
EII sector associations	✓	✓	✗	✗	✗	✗
Private consultant	✗	✓	✓	✓	✓	✓
Academic literature	✓	✗	✗	✓	✓	✓
Proprietary software	✓	✓	✗	✓	✓	?
Research gap	✓	✓	✓	✓	✓	✓

3. Proposed Methodology

DMAIC is a data-driven strategy of the quality management model Six Sigma; it consists of five phases—Define, Measure, Analyse, Improve, and Control—with the goal of process improvement (Coutinho, 2017a). SIPOC is a high-level, visual tool used in Six Sigma and lean manufacturing to map and define the boundaries of an entire process-improvement project according to its suppliers, inputs, processes, outputs, and customers (Coutinho, 2017b). DMAIC and SIPOC are often used together as two distinct tools in a hierarchical structure, where SIPOC forms part of the Define DMAIC phase to frame the process identified for improvement (Coutinho, 2017b). The carbon neutrality methodology proposed in this study for industrial organisations is presented as a DMAIC/SIPOC hybrid approach, where the SIPOC steps are mapped to phases of the DMAIC framework. The benefit of hybrid is that it has the advantages of each approach— DMAIC provides structure and defined outcomes, and the SIPOC details the process steps and clearly identifies the influencing factors of the process.

3.1 Adapted DMAIC Framework

The novel adaption of the traditional DMAIC framework is illustrated in Figure 1 and discussed thereafter.

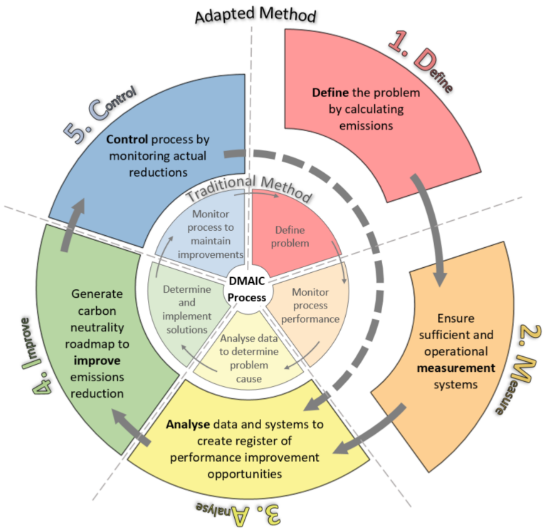

Figure 1: Graphical comparison of traditional and adapted DMAIC process

DMAIC Define: In traditional DMAIC, the problem is defined in this step as a qualitative input (Coutinho, 2017a). In the adapted approach, the qualitative problem—i.e. the organisation's use of emissions-generating energy sources—is known and is the driver for following the methodology. This step involves defining the extent of the problem (GHG emissions) as a quantitative input.

DMAIC Measure: In traditional DMAIC, this step represents the measurement of the process performance (Coutinho, 2017a). The adapted approach uses this step to ensure that the metering and monitoring systems are sufficient and operational, which includes checking that all relevant energy users are sub-metered, and that the meters are operational and record data with the optimal granularity for the process.

DMAIC Analyse: In both approaches, the measured data is analysed in this step. However, this analysis is used to determine the root cause of the problem in traditional DMAIC (Coutinho, 2017a), whereas it is used to create a list of energy performance improvement opportunities in the adapted method.

DMAIC Improve: In traditional DMAIC, the solution is determined and implemented in the improvement step (Coutinho, 2017a). This is similar in the adapted approach, however this step is more lengthy and complicated since the timeline from solution to full implementation is considerably longer. The solution is the output from the modelling tool in the form of a carbon neutrality roadmap of step-by-step improvements, expressed as an emissions-based waterfall chart. The implementation process is a number of steps in which the measures are implemented according to the roadmap timeline.

DMAIC Control: In traditional DMAIC, the control step occurs after implementation of the improvement to monitor the process and ensure that the improvement is maintained; if this is not the case, then the Define step is revisited and the cycle continues based on the new problem (Coutinho, 2017a). In the adapted approach, this control step overlaps the improvement step to ensure that the measures are implemented timeously and that the expected reductions are achieved after each step. This interplay between improvement and control is critical since a large negative discrepancy between the theoretical and practical results of any step must be accounted for further along the roadmap to reach carbon neutrality within the timeframe. If the theoretical targets are not reached after any step, the Analysis step is revisited to determine further energy performance improvement opportunities, and the cycle continues from this point.

3.2 Proposed SIPOC-DMAIC methodology

The new and novel adaption of the traditional DMAIC framework which was developed in this research is illustrated in Figure 2, and discussed thereafter. The customer listed in the final column is the person within the organisation, typically the energy manager, that is responsible for managing the carbon neutrality process.

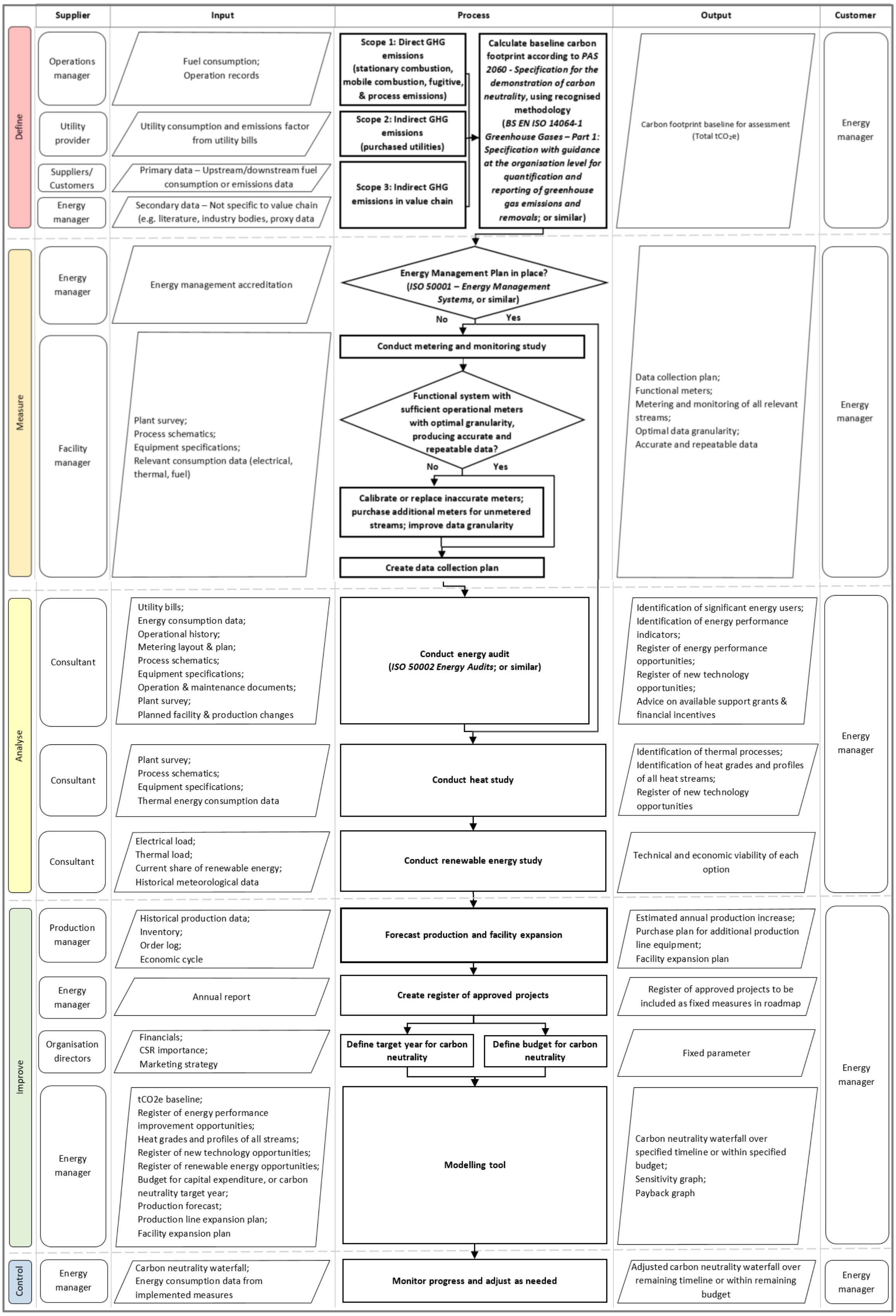

Figure 2: Methodology for carbon emissions neutrality in industrial organisations

SIPOC-DMAIC Define: The carbon footprint baseline is calculated as the total GHG emissions applicable for carbon neutrality assessment according to the global standard PAS 2060 (BSI, 2014). The total carbon footprint comprises scope 1 emissions calculated from fuel consumption and operation records; scope 2 emissions calculated using the consumption values in utility bills; and relevant scope 3 emissions using primary data measured from upstream and downstream sources, and secondary data where measurements are not possible or accurate. Note that scope 3 emissions under 1% of total emissions are currently not mandatory for organisations, but are included in the methodology with reference to PAS 2060 which may be updated in future. The carbon footprint is calculated using a recognized methodology, such as BSI (2019).

SIPOC-DMAIC Measure: This step ensures that the metering and monitoring systems are sufficient to facilitate collection of the energy consumption data required for the Analyse step. All relevant processes must be metered by functional meters that record and monitor data effectively at an appropriate granularity for each process. This is achieved by surveying the plant and equipment on site, examining the process schematics and equipment specifications to identify the processes to be metered, and analysing relevant consumption data. This information is used to formulate a data collection plan to document the process and ensure consistency in data collection with accurate, repeatable data. This step can be bypassed if there is an energy management plan in place—e.g., ISO (2018)—as this incorporates a data collection plan which meets the requirements of this step.

SIPOC-DMAIC Analyse: This step comprises the following three activities to yield inputs for the modelling tool:

- Energy audit - An energy audit in accordance with a relevant standard such as ISO (2014) uses utility bills, energy consumption data, operational history, metering layouts, process schematics, equipment specifications, operation and maintenance documents, plant surveys, and planned facility and production changes to identify the significant energy users (SEUs), and energy performance indicators (EPIs). SEUs have the greatest potential for energy reduction, and EPIs normalize energy consumption for continuous monitoring to optimise efficiency. However, the primary function of the energy audit in this methodology is to generate registers of energy performance improvement (efficiency) and new technology (equipment) opportunities. Additionally, it advises on available grants and financial incentives for specific measures, for use in the financial analysis of the modelling tool.
- Heat study - A heat study uses plant surveys, process schematics, equipment specifications, and thermal energy consumption data to identify the thermal processes, heat grades and profiles, and the heat recovery barriers of specific streams owing to physical limitations (plant layout) and other factors.
- Renewable heat study— A renewable energy study uses the electrical and thermal loads, current share of renewable energy, and historical meteorological data to generate technically and economically feasible renewable energy options for further analysis within the modelling tool.

SIPOC-DMAIC Improve: This step considers focuses on the modelling tool, and its additional inputs.

- Production forecast and facility expansion – It is important to map the future energy requirements over the carbon neutrality timeline to ensure that the emissions abatement measures are futureproofed against possible changes in production and facility expansion. Production can be forecast using trends in historical production data, inventory, order logs, and knowledge of the economic cycle. Planned purchases of additional production lines and facility expansion should be noted. This information is input into the model to accurately scale up the organisation’s energy requirements.
- Approved projects - A list of approved or in-progress measures for increased efficiency, heat recovery, purchase of new equipment, and investment of further renewable energy is required for input into the modelling tool. These are planned projects that will be implemented regardless of the outcome of the carbon neutrality roadmap, and that will affect the non-renewable energy consumption.
- Define fixed parameter - The fixed parameter should be set as the budget (total and/or annual capex funds available for emissions-saving measures over the carbon neutrality timeline) or the target year. The modelling tool incorporates scenario modelling to consider the effect of fixed parameter type and quantity.
- Modelling tool - The outputs from the Analyse step and the initial stages of the Improve step form the model inputs. The model’s built-in inputs include current and future carbon tax and the minimum future renewable energy mandated by country policy. The model uses the graphical process integration tool of pinch analysis on the heat grades and profiles identified in the heat study to propose heat recovery opportunities. The user can switch off any of the emissions-reduction measures and change the cost parameters (inflation rate, carbon tax rate of increase, renewable energy cost and rate of increase, utility cost and rate of increase, carbon offset cost and rate of increase) to study the effect. The model prioritises emissions-reduction measures in the order of efficiency, heat recovery, new technology, and renewable energy to generate an emissions-based carbon neutrality waterfall, and a payback graph to determine the breakeven point, and a sensitivity graph to determine the inputs with the greatest effect on emissions reduction.

SIPOC-DMAIC Control: The energy consumption data is used to calculate the total carbon footprint after implementation of each measure to compare the theoretical and actual progress. The total footprint must be used to consider the interaction effects of the independent emissions-reduction measures. Regression analysis such as ‘Option C – Whole Facility’ of the International Performance & Verification Protocol could be used for this calculation to normalize the results against the baseline to determine the efficacy of each measure (IPMVP, 2002). However, the absolute emissions also need to be calculated to control the carbon neutrality process, where emissions-saving measures are added to the waterfall if required to compensate for shortfalls.

4. Conclusions and Future Work

This work highlights the scope for a highly detailed, open access, cross-sectoral methodology and associated toolkit at the organisational level. A hybrid DMAIC-SIPOC methodology for carbon emissions neutrality of industrial organisations is presented. A supporting model is introduced, where the outcome is an emissions-based waterfall to carbon neutrality, as well as sensitivity and payback graphs. Future work includes further developing the supporting modelling toolkit, and verification through a case study of a medical device manufacturing facility.

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