INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.135

# Alignment of the functional structure with sustainability aspects in product development – combining the strengths of the functional structure with the MECO matrix

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**Abstract**

Many of the methods and tools proposed in the literature for validating product concepts are matrix-based, but they do not allow the results to be communicated easily and comprehensibly. This is a major obstacle to the integration of such methods. The poor communication of the results of a method therefore represents great potential for better integration of sustainability aspects in product development. In this article, an approach is proposed on how the results of the MECO matrix can be converted into a clear visualization of the reduced environmental assessments.

*Keywords:* *MECO-matrix, function structure, product development, sustainable design, methodical design*

## 1. Introduction

Many methods and tools (summarised in the following as techniques) are proposed in the ecodesign literature to help validate the sustainability of products or concepts. For small development groups and small and medium-sized enterprises (SMEs), such light LCA (Life Cycle assessment) techniques are primarily suitable due to limited capacities. Many of these techniques are matrix-based, but they do not allow the results to be communicated easily and quickly which is key for lasting impact within a team and thus for a sustainable long-term development either in a product scope and also within the society. Among other things, this is a major obstacle to the integration of techniques in SMEs that are focused on sustainability. Better communication of the results of a technique (Guérineau et al. 2018) thus represents a great potential for better integration of sustainability aspects into the product development (PD) of SMEs and therefore enabling developers shifting focus on sustainability more easily.

In this contribution, an approach is proposed for combining the results of the MECO matrix with the functional structure to provide a clear and easy-to-understand visualisation of the results of a reduced and preliminary environmental assessment using the MECO matrix. This is implemented in the form of influences and effects, which provides the opportunity to influence the sustainability of the development in a targeted manner over the entire product development process. For this reason, the basics of the techniques are briefly and concisely explained below and further literature is referenced before the synthesis of the techniques is presented.

## 2. State of the art

There are a number of tried and tested techniques for evaluating products, product variants and/or concepts in the early phases of product development. These include qualitative techniques such as the

Eco-Design-Checklist, the QFDE (Masui et al. 2003), (Sakao 2007), MET matrix (Brezet et al. 2001), (Tischner and Moser 2015), (Bhamra and Lofthouse 2007) and the MECO matrix (Pommer et al. 2003), (McAloone and Bey 2009), (Wenzel 1998), (Pommer et al. 2003) as well as methods supporting interdisciplinary collaboration like the integrated function modelling framework (Eisenbart et al., 2017). The Integrated Function Modelling Framework as a further development of the function structure is a method for modelling and analysing the functionality of technical, medium complex systems. It aims to combine different functional modelling perspectives from different disciplines in one chart to give a holistic view of the system's functionality. The matrix-based MET and MECO can be used to create a simple but comprehensive overview of possible problem types throughout the entire life cycle of the product being analysed. The QFDE could also be used well for this purpose, but does not appear to be applicable within the contribution concept due to the high complexity of the method itself. The Eco-Design Checklist is used more for project orientation, whereby the aspects can also be used to analyse product concepts, which is why this technique is not used in the contribution. The MECO matrix crystallises here as a more comprehensive but also easier to use technique. It is therefore regarded in detail below.

## 2.1. MECO matrix

The acronym of the MECO matrix according to Wenzel (1998) is formed by the categories *Materials*, *Energy*, *Chemicals* and *Other*. The information on the product life cycle of a product development forms the basis for the MECO matrix when analysing the product. It is visualised using a reduced diagram in which the life cycle phases (Figure 1) and the causes of the environmental impact are shown visually. The advantage of the MECO matrix is that the individual causes of environmental impacts do not overlap and that it covers all significant environmental aspects. This makes it possible to assess whether there are any problems that need to be solved by further development, e.g. with regard to energy consumption or the use of chemicals.


**Figure 1. Life cycle phases of a product (Stefanov 2017)**

For each category, ecological aspects of the individual product life cycle phases are critically analysed and recorded (Table 1). A rough outline of the categories is provided below for a better understanding:
The "Material" category includes all materials and resources required to manufacture, use and maintain the product. Materials that are reused in the disposal phase are entered in the disposal field and labelled with a minus sign. The use of materials is shown partly as a quantity and partly as resources.
The "Energy" category includes all energy consumed during the life cycle of the product, including the energy used in the provision of materials. Energy use should be reported as primary energy and as use of petroleum resources. The consumption of energy is calculated as consumption of petroleum resources.
The "Chemicals" category includes all chemicals in the life cycle of the product. Chemicals are categorised as type 1, 2 or 3 depending on their environmental hazard. Type 1 refers to very problematic substances, type 2 to problematic substances and type 3 to less problematic substances. The classification was made with the help of EU directives on the labelling of chemicals (Council Directive 67/548/ 1967) and Danish lists (Listen over uønskede stoffer 2009 2010). A chemical is categorised as type 1, 2 or 3 depending on whether it is included in both, one or neither of these lists. Environmental impacts that cannot be categorised as described above are included in the "Other" category.
(Pommer et al. 2003), (McAloone and Bey 2009), (Wenzel 1998)
The materials and manufacturing processes used are thus recorded in order to enable the simple determination of quantitative values for resource and energy consumption. Pommer et. al provide simple lists for the data to assess the implementation of a MECO matrix (Pommer et al. 2003). This makes it possible to compare the environmental impact of the individual product life cycle phases without having to carry out time-consuming research and calculations beforehand, for which SMEs usually lack the capacity and/or resources.



https://doi.org/10.1017/pds.2024.135 Published online by Cambridge University Press

Table 1. MECO matrix analysis of a coffee machine according to (Pommer et al. 2003)

| | Raw materials phase | Production phase | Use phase | Disposal phase | Transport phase |
|---|---|---|---|---|---|
| **Raw materials** Quantities | PS: 1.12 kg<br>PVC: 0.02 kg<br>Glass: 0.34 kg<br>Cardboard: 0.39 kg<br>Aluminium: 0.11 kg<br>Copper: 0.02 kg<br>Steel: 0.3 kg | Release agent<br>Lubricant | Paper: 7.3 kg<br>Coffee: 290 kg<br>Water: 3.690 kg | | |
| **Resource** consumption | Crude oil: 0.022 mPR<br>Natural gas: 0.022 mPR<br>Al: 0.17 mPR<br>Cu: 0.33 mPR<br>Fe: 0.0024 mPR<br>Mn: 0.015 mPR | | | Fe: -0.012 mPR<br>Mn: -0.008 mPR | |
| **Energy** Primary | 154 MJ | 96 MJ | 9.656 MJ | -4.541 MJ | 2.968 MJ |
| mPR (crude oil) | 0.15 mPR | 0.09 mPR | 9.42 mPR | -4.43 mPR | 2.90 mPR |
| **Chemicals** | Fluorides used when manufacturing aluminium.<br>Heavy metals used when making copper.<br>Vinyl chloride monomers used for making PVC. | Crude oil distillates (undesirable?)<br><br>Hydrogen peroxide (C, R34) | Acetic acid (C, R34) | | |
| **Other** | Extraction of metals, working environment issues | Die casting of PS, amanations | Decalcification, odours from acetic acid | Not known | No comments |

Once the MECO matrix has been completed, it must be assessed whether it provides a sufficient basis for answering the questions posed in relation to the product to be developed or whether the analysis of the product or concept needs to be continued. The analysis using the diagram can be followed by a comprehensive life cycle assessment later in the product development process, which enables a more detailed evaluation of the product. The MECO matrix has already identified the main focal points and all inputs and outputs for each category can be analysed on the basis of the functional unit and the selected life cycle phase.

To make it easier to compare products, material and energy consumption can be calculated as resource consumption in milliperson reserves (mPR). A person reserve is a resource, consumption in relation to the global reserves of one, which is available for one person and all future descendants. (Pommer et al. 2003), (Hochschorner and Finnveden 2003)

**Procedure**

A matrix is created based on the requirements for the product or the development task. It is possible to draw a 4x5 matrix (expandable if necessary) on a whiteboard or to record data directly in an Excel spreadsheet. When working with a whiteboard, the previously recorded data can be written on post-it notes and then assigned to the respective life cycle phases and, if necessary, assigned to another category if it is determined in the discourse that a new placement makes sense. Each environmental impact is considered in turn and assigned to the most relevant field. If an environmental impact relates to two or more fields, several post-it notes are assigned to the fields. The matrix can then be adjusted in dialogue with the team and individual post-it notes can be moved.



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After this first step, the MECO matrix is discussed again by the development team. Subsequently, certain environmental impacts within each MECO field can be summarised if strong correlations are recognisable and/or reclassifications are made.
One way of identifying the most important environmental focal points is for a development team to carry out a discursive assessment by awarding "stars". The most important challenges to be solved are identified by awarding 1-5 stars, whose values become defined by the development team.
The MECO matrix thus provides an initial analysis of the current situation, a reference product or a product concept, from which focused further development can take place in light of the identified weaknesses. Furthermore, the MECO matrix can be used as development progresses to compare the initial situation with the advancing product and identify any new problems that may arise.

## 2.2. Functional structure

The functional structure breaks down a complex overall function of a product development into smaller sub-functions, organises them logically and identifies relationships. The technique is used to describe the system of functions and product properties and emerged by the Structured analysis and design technique (SADT) developed by Douglas Ross (Ross et al. 1977) . It supports the synthesis and analysis of products and enables the systematisation of functional relationships (Ehrlenspiel and Meerkamm 2017). This will simplify the subsequent search for a solution. This requires a sound understanding of the task and the underlying problem.
The functional structure serves as a graphical sectional representation of the overall function of a system or product. The individual sections reflect sub-functions that are related to each other through energy, material and signal flows (operands) and linking rules (operations): storing, conducting, transforming, converting and linking (Figure 2). General variables can also be represented in flow structures (Ehrlenspiel and Meerkamm 2017). Care must always be taken to formulate the sub-functions in general terms to avoid fixating on specific proposed solutions.

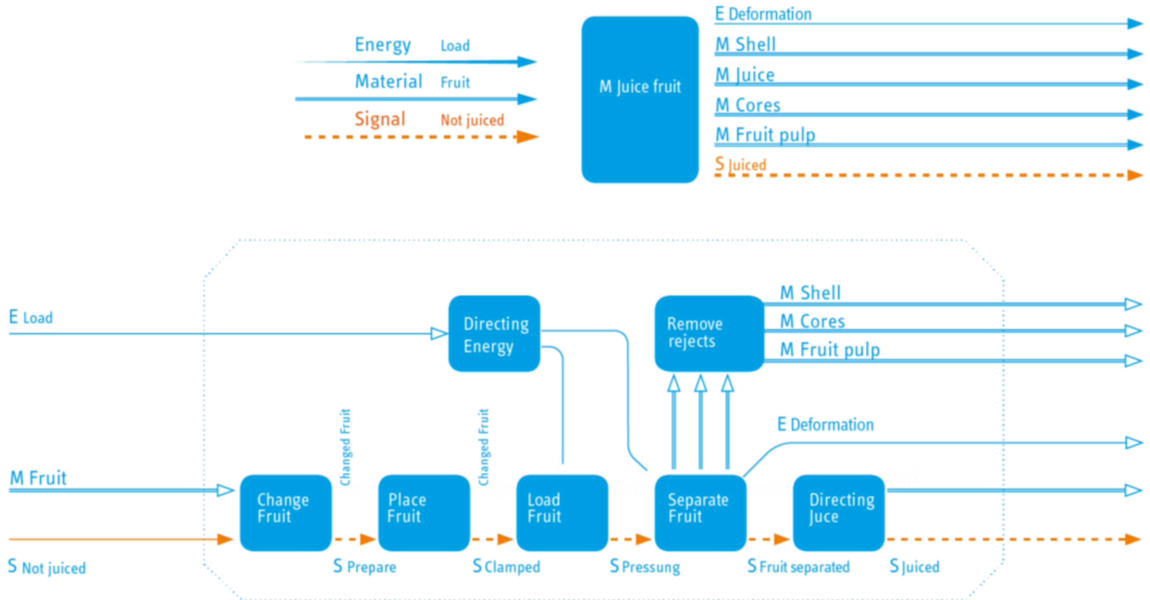


**Figure 2. Example of a functional structure**

The relationships between the input and output variables of the system are shown and system limits are defined. Through the iterative approach, the operands presented are networked more finely and a clear understanding of the system under consideration is gained, whereby the complexity should always remain appropriate to the task at hand. (Gericke et al. 2021), (Grothe et al. 2011).
Due to the iterative approach, the functional structure is associated with a high workload. However, it can serve as a basis for further developments or variant designs, so that the effort is minimised in the following. It shall be noted that it is not possible to visualise the conversion of the general variables of substance, energy or signal into each other.



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If there is no energy or material flow in an overall system, less complex structuring techniques can be used as an alternative. Furthermore, it is possible to dispense with a functional structure after a fully recorded utilisation scenario if the essential product processes have already been defined - a functional structure would therefore not generate any new benefits.

**Procedure**

Function sets are formulated from the list of requirements, which is a list of necessary product requirements by the development team, consisting of product specifications, user needs and production parameters. These requirementsare then abstracted and assigned to general functions. To visualise the initial situation, the input and output variables of the overall function are first defined. This is then broken down iteratively into less complex sub-functions and linked by the operands. This results in a simple, clear and general function structure. The main flow of the overall function is the task core, which must be supplemented piece by piece with tributaries. For complex structures, it is advisable to create smaller functional units with separate functional structures.

Structural variations by splitting and merging sub-functions and changing the sequence or system boundaries help to find solutions and optimise requirements (Gericke et al. 2021).

In this way, the functional structure helps to find solutions and supports the expansion of the developers' understanding. It can be used for new developments as well as further developments, whereby the procedure differs. It seems sensible to work out the function structure in loops, whereby it is recommended to proceed from rough to complex structures.

## 3. MECO functional structure - Synthesis

In this contribution, the functional structure is proposed as a means of visualising the results of a MECO matrix analysis in a clear and easy-to-understand way, as any flows can be clearly represented for the individual life phases. This leads to a more focused and aim oriented decision making due to an easy and understandable reflection of the targeted product development resulting in a higher possibility to influence the prospective effects on the environment. Depending on the task at hand, a different application might apply best to each scenario, a MECO for life cycle for example could be applied for a long-term-evaluation of a product.

### 3.1. Application purpose and principle

The procedure for the application of this MECO functional structure is divided into the following two main areas. A conventional MECO matrix is developed as the basis for creating a MECO function structure. This is followed by the visualisation of the results analogous to a functional structure. The life cycle phases raw material phase, production phase, utilisation phase and disposal phase are implemented as nodes in a flow chart (Figure 3).

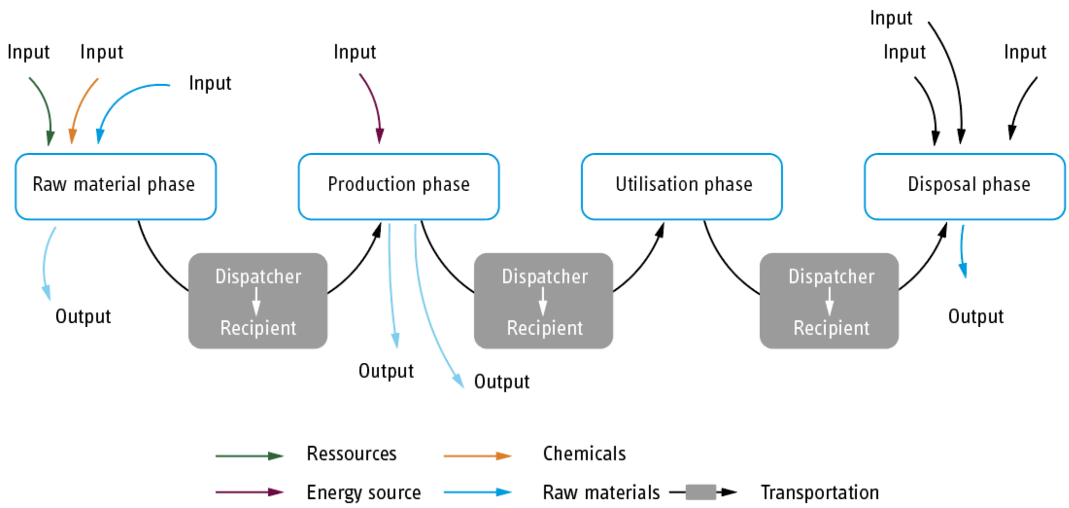


**Figure 3. Example of a MECO functional structure**



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The ecologically relevant factors run through the diagram in the form of arrows, which are assigned/defined/highlighted in colour depending on the category from the MECO matrix and characterised by an associated legend. This shows the flow of dynamic relationships within the system, for example through the conversion of chemicals in the raw material phase for the production phase, which enters the utilisation phase as a finished product and finally emerges from the disposal phase as energy and pollutant emissions through incineration.
The detailed procedure for the creation can be based on the following tasks:

1. Identifying the main functions
   Firstly, the main functions of the system are identified and visualised in the functional structure. This can already be organised according to the life cycle phases relevant to the product or system or can first be shown in a tree diagram.
2. Analysing the interactions
   The interactions between the main functions are then analysed. The MECO matrix can be used here to visualise the relationships between the functions.
3. Combining the information
   The essential step is to combine the information into a holistic diagram of the inputs and outputs in view of the product's life cycle stages. The synthesis makes it possible to clearly identify neuralgic "points" of the system and where these can be counteracted.
4. Evaluating the interactions
   The interactions between the functions are assessed to determine their significance and impact on the system. This can be done, for example, by using weighting factors or prioritisation.
5. Optimising the system
   Measures for optimising the system can be derived based on the results of the interaction analysis. This can include, for example, rearranging or adapting the functions in order to minimise or optimise the interactions.

This leads to the research hypothesis that by combining the MECO matrix with the functional structure, complex systems can be analysed, optimised and structured by taking into account both the functions and their interactions. This enables a holistic view of the system and supports the development of efficient solutions. Furthermore, a combination of a classically performed function structure with the results of a MECO function structure can provide further insights into open development potential.

## 3.2. Prototypical application of the MECO functional structure

The presented technique has been applied in a case study within the interdisciplinary Master's programme Integrated Design Engineering (IDE) with the aim to develop a new product using the company's previous waste materials. The focus was on the further utilisation of waste material and no specific product was envisioned, which is why the development team was free to design completely different product alternatives which lead to different results of the analyses. Within the IDE product development approach the analysis took place in two (the first and last) of four typical development phases. The IDE process model proposes a four-phase division (initialisation, conceptualisation, detailing and realisation) within a project for the structured and activity-related realisation of development tasks. (Vajna 2022)
The project set-up consisted of an interdisciplinary student team of six to eight and two teachers to coach the team over the course of a 14-week semester. Two meetings a week were set to discuss progress and individual assignments and tasks as well as teamwork, each meeting shadowed by one teacher to give input and guidance when needed. The rest of the week the team worked independently, amounting to about 10 hours per person.
In the initialisation phase, the initial situation was recorded by creating an environmental profile, while in the realisation phase, the initial situation is compared with the final realisation of the concept. In Figure 4 it is illustrated one of the results in the beginning phase of the project to analyse the initial situation. At the beginning of the life cycle, substances such as crude oil and natural gas are required as resources and an energy input of 35 MJ/kg for the production of PVC (Pohle 1997). Additional chemicals such as phthalates are used as plasticisers to modify the properties. The PVC obtained is then delivered to the company by a supplier. Chemical energy is converted for transport, which emits CO2 into the environment. At the

company, other resources such as yarn or haberdashery are used to produce the product portfolio. The output is offcuts and the actual product. As information on MECO aspects after delivery to customers and from customers to the landfill is difficult to collect, it can only be generally stated that each transport requires energy and therefore releases CO2. As soon as the PVC material is no longer needed in the utilisation phase, it is sent to the disposal phase. There, the PVC is thermally utilised and a calorific value of 18 MJ per kilogram is produced (Schmitt and Vetter 2001). During incineration, toxic and harmful substances are produced in the form of chemicals such as carbon dioxide, nitrogen monoxide and so on.

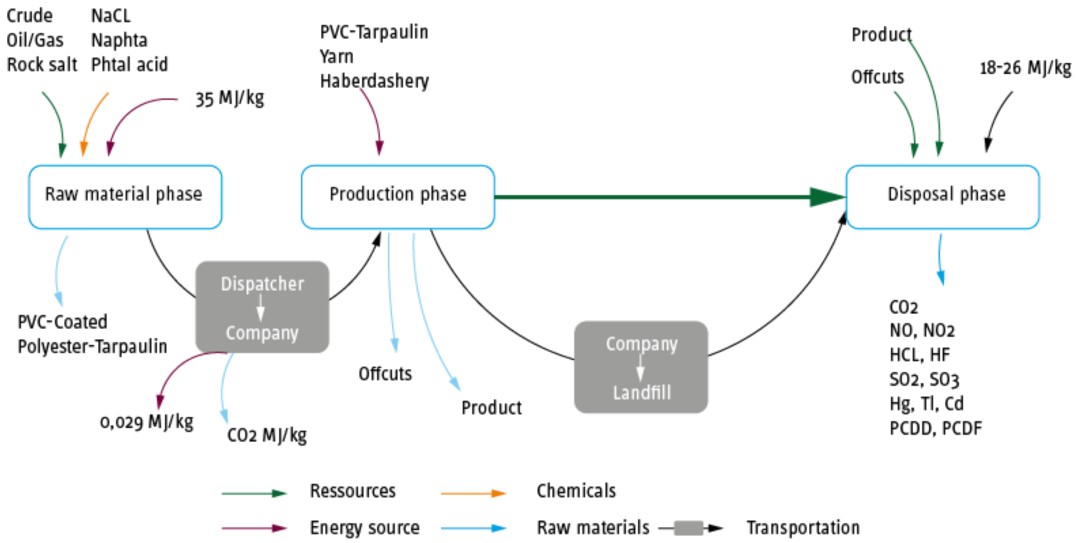


**Figure 4. Results of the application of the MECO functional structure in the initialisation phase**

As in the initialisation phase, the factors specified by the MECO matrix - materials, energy, chemicals and others - are considered over the expected life cycle of the developed product concepts. Similar to the procedure for the first technique application, the known factors are recorded qualitatively or quantitatively depending on their availability and visualised in a functional structure. Due to the planned utilisation of offcuts from existing production, the process shown in Figure 5 is based on the previous MECO functional structure created in the initialisation phase. Several changes have been made to account for learnings made in the previous development phases. Instead of allowing the material to flow directly into the disposal phase, it is fed back into production and upgraded into new products. The structure clearly shows that by marginally expanding the existing flow of goods at the company, including the provision of Velcro tape, eyelets, buckles, pegs and thread, it is possible to ensure that the previously unused discarded material can remain in circulation as a product.

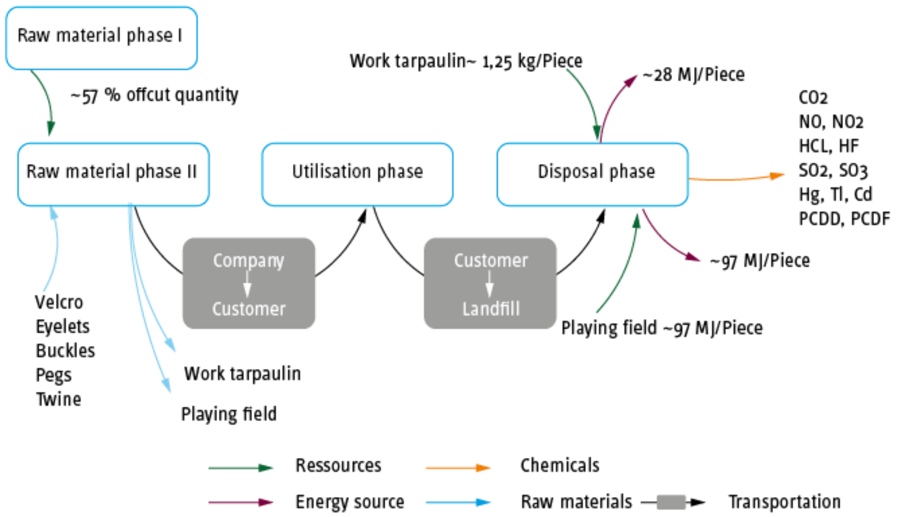


**Figure 5. Results of the application of the MECO functional structure in the realisation phase**



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The products only enter the disposal phase after an extensive utilisation phase and the associated wear and tear. As in the case of offcuts, the PVC tarpaulin used is expected to be thermally utilised, which results in the corresponding energy and pollutant outputs. The energy output per unit is calculated by multiplying the weight of a unit by the energy yield per kilogram of PVC tarpaulin, which can be taken from the MECO matrix for initialisation. In contrast to the previous approach, the materials are treated according to the principle of maximisation, in that the maximum benefit is obtained from the available material before it is disposed of. The waste of resources can thus be better justified. The elimination of the raw material phase for the new products is a further improvement: by using the offcuts of previous products for production, additional transport routes are eliminated and emissions and energy sources are saved.

### 3.3. Findings

The application is based on the modified visualisation of the results as a functional structure. Project-specific factual knowledge on environmental and waste factors was compiled by the developers and thus supported the application. It was shown that the application raises complex questions about the sustainability of the development task and that learning success can be achieved by answering these questions. However, the time required was between ten and fourteen working hours. The familiarisation time was just as long as the application time. This is due to the previously unknown procedure and can probably be reduced to a large extent in further applications. It is also conceivable that specialised users will come together in sub-groups and discuss their results with the development team. As a result, the developers receive the environmental profile of the initial situation and the respective concepts, which makes it possible to record the initial situation and compare the subsequent realisation. Table 2 illustrates the framework data of the application within the prototypical application.

**Table 2. Results of the application of the MECO functional structure**

| | |
|---|---|
| Target | Initialisation phase: Recording the initial situation and creating an environmental profile of the product/concept<br>Realisation phase: Comparison of the initial situation with the final realisation of the concept |
| Time required | Familiarisation approx. 5-7 h<br>Execution approx. 5-7 h<br>Additional research > 2 h |
| Time of application | Initialisation phase: From the start of the project<br>Realisation phase: As soon as all the necessary information regarding the final concept is available |
| Prerequisite | Comprehensive factual knowledge of environmental factors and waste factors |
| Realisation | Comprehensive factual knowledge of environmental factors and waste factors<br>Visualisation as a functional structure to better communicate the results (Figure 4) Inputs and outputs of the respective phases are recorded and presented with their effects in order to provide a quick and easy overview of the classification in the product life cycle and the application, as well as heavy consequences |
| Procedure | Developed and finalised in a subgroup of three developers (specialist group) |
| Result | Environmental profile of the product/concept in form, visualised as a functional structure<br>Communication basis within the project team as well as for the cooperation partner |

## 4. Conclusion and outlook

The concept presented represents a further development of the MECO matrix and optimises the technique in terms of the easy-to-understand visualisation of the results. However, the application of this technique requires more time resources than the original version of the MECO matrix. To reduce the time required, a combination of the MET matrix according to (Bhamra and Lofthouse 2007) with the functional structure can be an option. The procedure can be based on the concept described above and can nevertheless enable faster implementation, as the MET matrix application requires fewer resources than the MECO matrix application. It is also conceivable that a semi-automated implementation of the results can be carried out on an already created table template for carrying out a MECO matrix analysis. However, the feasibility of this must be qualified and determined in the further course.

A hurdle for the successful application is that a qualitative assessment such as this of the MECO functional structure is faster than a quantitative one, but can also be misleading if the assessment is carried out by non-experts.

This technique can cause difficulties by providing easy-to-use tools (that anyone can use without much time or experience) that give the false impression that even an easy-to-create LCA (Life Cycle Assessment) technique can be performed by non-experts, when in fact it is intended to simplify a very complex assessment. With this knowledge and the orientation of the developed technique towards the early phases of product development to analyse the weak points of a reference product or to evaluate product concepts, the aforementioned problem can be avoided. It shall also be noted that the application of simple and more quickly usable techniques builds up expertise within the company, which contributes to more sustainable development in the long term.

However, the prototypical application within a product development brought the great advantage of an easily understandable visualisation of the results of the analysis carried out. This made it possible to conduct a quick and simple discourse with stakeholder decision-makers and to resolve development-relevant decisions by consensus. This is probably the greatest achievement of the proposed technique.

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