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Information-based Integration of Life Cycle Assessment into IT Landscapes of Manufacturing Companies

Martin Perau*, Niklas Laubach*, Tobias Schröer*, Wolfgang Boos*, Günther Schuh*

*Institute for Industrial Management (FIR) at RWTH Aachen University, Aachen, Germany (Tel: 0049-0241-47705-416; e-mail: martin.perau@fir.rwth-aachen.de).

Abstract: Life Cycle Assessment (LCA) is one of the fundamental methods to facilitate effective decisions in sustainability transformation. However, the current implementation of LCA is inefficient due to detached software applications and manual data imports. Utilizing data from existing information systems offers the potential for a significant increase in efficiency. Existing approaches focus on prototypical implementations with a high level of detail but low transferability, or approaches only consider integration at the system level, whereby practical applicability is reduced. Therefore, this paper presents an information-based framework for integrating LCA software into the existing IT landscape of manufacturing companies with focusing on generic functions and a detailed information flow. The generic approach enables transferability, while the detailed information flows allow practical applicability.

Keywords: Life Cycle Assessment, Sustainability, Information system, IT landscape, Integration

1. INTRODUCTION

Climate change is one of the biggest threats to people around the world. According to the World Economic Forum Global Risks Perception Survey 2022-2023 results, climate-related and nature-related risks occupy the leading positions in perceived importance in the coming decade (World Economic Forum 2023). More and more business acknowledge their responsibility to embed sustainability principles in their corporate activities (Arndt et al. 2018). Manufacturing companies, in particular, account for approx. 30% of global greenhouse gas emissions, so there is a great need to take appropriate measures to encourage a sustainable transformation (Rusche et al. 2021).

A toolbox of sustainability management methods is required to assess actions from an ecological perspective and make decisions based on proper environmentally relevant information (Tschandl and Posch 2012). One widely used method is life cycle assessments (LCA), which can be used to evaluate products, services, and processes from a sustainable perspective (Funk et al. 2013; Funk and Niemeyer 2010; Tschandl and Posch 2012). The quality of the ecological assessments generated with the help of LCAs depends directly on the quality of the information included (Saxce et al. 2012). Since LCAs are usually carried out with the help of stand-alone specialized software, information must be collected from many different sources and entered into the LCA software manually. This leads to numerous efforts and can result into a lower data quality (Saavedra-Rubio et al. 2022). To simplify the process of collecting information for the creation of an LCA, it must be ensured that information already available for the LCA software is integrated. Already established information systems of manufacturing companies, such as enterprise resource planning systems (ERP) and manufacturing executions systems (MES), could be used as data suppliers for ecological relevant information. For example, over 40% of the necessary information for CO_2-Accounting can be gathered from a ERP system (Perau et al. 2023). The desired integration of LCA software into the IT system landscape of manufacturing companies will enable more efficient implementation of LCA. Integrated LCA software is intended to offer the possibility of using a high degree of automation to evaluate products and processes (Minhas and Berger 2014).

The basis for integrating LCA software is a conceptual interlinking of the functions of the LCA software with other information systems, considering the necessary input information and the potential sources of this input information. The paper aims to present an information-based integration framework between LCA software and manufacturing companies' existing IT landscape. This generic description serves as a blueprint for subsequent company and IT-specific integration. The paper is structured in six chapters, with the first chapter forming the thematic introduction. The second chapter of the paper describes the theoretical foundations regarding life cycle assessment and IT landscapes of manufacturing companies. Next, the state of the art of integrated LCA is analysed. Chapter 4 describes the applied method and chapter 5 presents the final integration framework. Finally, the results are summarised and the further required scientific actions are discussed.

2. THEORETICAL BACKGROUND

2.1 Life-Cycle-Assessment

According to DIN EN ISO 14040, Life cycle assessment (LCA) refers to the method of calculation environmental aspects and potential environmental impacts during the life cycle of a product from raw material extraction production, use, waste treatment, recycling, and final disposal (DIN EN ISO 14040). LCA consists of four main phases.

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Phase A describes why the LCA is being carried out. It also defines the framework required to achieve the objective of the life cycle assessment study. For this purpose, the system under consideration is determined with the associated system boundaries (e.g. gate-to-gate). (DIN EN ISO 14040)

In the inventory analysis (Phase B), all inputs and outputs are recorded, taking into account inputs and outputs that flow into or out of the system in the form of material and energy flows (Hauschild et al. 2018). The system under consideration can be divided into sub-processes to model it. A unit process is defined as the smallest possible aggregation for which inputs and outputs can be described (Hauschild et al. 2018).

The first step a the impact assessment (Phase C) is selecting impact categories, indicators, and characterization. An impact category describes an effect on the environment, for example, climate change. A characterization model is used for elementary flows, such as CO_2 emissions to be converted into impact indicator values using a characterization model. The second step assigns the life cycle inventory results to the selected impact categories. Next the impact indicator values are calculated using the selected characterization. These steps can be automated and can usually be carried out efficiently in LCA software. (DIN EN ISO 14040; Hauschild et al. 2018)

As a final step, the results of the previous steps are interpreted (Phase D). Additionally, Quality control is carried out by checking the results for completeness and consistency. LCAs are typically used as a basis to facilitate decisions or reporting purposes. For this purpose, LCAs are used to create hotspot analyses or determine ecological footprints (Del Borghi 2013).

2.2 IT landscapes of manufacturing companies

An IT landscape is an ensemble of different, individual information systems that are organised in such a way that they efficiently support the business objectives (Winkler and Gilani 2010). An information system, often abbreviated as an IT system, is defined as a socio-technical system that supports business objectives by communicating and processing information (Vogel 2008).

For a suitable IT landscape that enables competitive processes, the data dependencies between the respective information systems must be considered when designing the IT landscape (Hanschke 2010). To achieve this goal, it is essential to integrate the systems with one another. This integration encompasses various aspects, including the integration of data or information. This involves the conceptual, logical, and/or physical merging and exchange of data, allowing it to be utilized by diverse entities within the IT landscape (Kurbel 2021). Among the various information systems, enterprise resource planning systems (ERP systems) are extensively employed information systems in manufacturing companies. (Statistisches Bundesamt Deutschland 2021). An ERP system oversees, plans, documents, and controls the business processes and resources within an enterprise (Munkelt and Völker 2013). Therefore, a ERP system is recognized for its diverse and wide set of functionalities (Külschbach 2021). Another information system frequently used by manufacturing companies is the Manufacturing Execution System (MES). MES links the ERP system and machines at shop floor level (Kletti 2015). Due to the real-time and control capability of MES, they are an instrument in production to react efficiently to events such as disruptions and deviations in the operation to be able to react efficiently (Kletti and Schumacher 2014). The data required for this can often be collected fully automatically via direct to the machines or semi-automatically via terminal inputs (Barton et al. 2018). In addition, there are other product-centred information systems within manufacturing companies: computer-aided engineering and product life cycle management systems. These systems are not the focus of the paper, as the study focusses on systems with a focus on business processes.

3. STATE OF THE ART OF INTEGRATED LCA

The topic of integrating LCA with existing information systems has already been discussed in existing scientific literature. MINASH AND BERGER propose a web-based tool for connecting LCA software and information systems based on a specially developed software architecture to simplify the performance of LCAs (Minhas and Berger 2014) (S1). Explicit information to ensure integration is not described within this approach.

FUNK AND NIEMEYER present an architecture for integrating of ERP systems and business environment information systems with LCA databases. An integration platform is proposed for this purpose, via which the information systems of companies can relate to external LCA tools and information systems of customers and suppliers (Funk and Niemeyer 2010) (S2). The focus is on presenting the overall concept rather than describing the integration by using information.

YOUSNADJ ET AL. describe a methodology for linking a tool for carrying out a simplified LCA with PLM and ERP systems. The focus here is on the implementation process and not on conceptualizing a solution. (Yousnadj et al. 2014) (S3). Information systems and LCA software are considered generically, and the functional modules and required information are not addressed.

ZHOU AND TOA present a conceptual architecture of a CAX/PLM/ERP-LCA system. They identify challenges regarding the data flow between the system components and propose the functional requirements of the system (S4). (Zhou and Tao 2021) Nevertheless, generalisation at the information level does not exist within the concept.

FERRARI ET AL. presents a dynamic life cycle assessment (Dynamic LCA) system that utilises real-time data from ERP systems for environmental assessments in the manufacturing industry. This system is tested and validated using an Italian ceramic tile manufacturer to demonstrate its effectiveness in practice (S5). (Ferrari et al. 2021) However, the used information is not generalised and described independently of the industry.

TAO ET AL. presents a prototype LCA tool based on bills of materials and IoT technology. The required information and functional modules of IT systems are described in detail (S6). (Tao et al. 2014) However, the paper's objective differs from the objective of this paper in that the development of a new system is presented as a solution approach and not the integration of existing LCA Software.

Figure 2 shows the focus of the respective sources (S1 to S6) and illustrates the resulting research gap. Previous approaches clearly show the potential of an integrated LCA (S1) or explore the integration between LCA and other information systems (S2, S3, S4) by looking at entire systems. These approaches are general and enable transferability between industries. In addition, extensive studies on prototypical or company-specific approaches (S5, S6) impressively validate the concept of integrated LCA. These provide a high level of practical applicability.

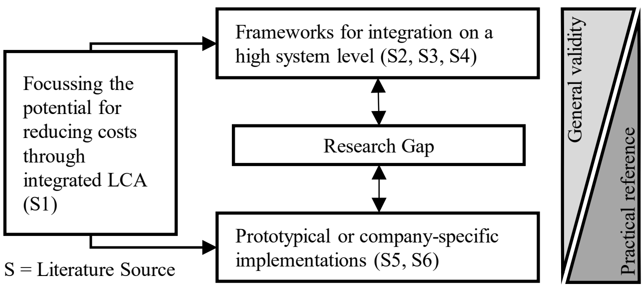

Figure 1 Identified Research Gap

The research gap lies between these two types of approaches. For a more comprehensive establishment of an integrated LCA, a generic approach but also with a higher level of detail and, thus, practical applicability is needed. This requires describing an integration approach considering individual generic functions and information flows, which is the focus of this paper.

4. APPLIED METHOD

Based on the aim of developing an information-based integration framework, modeling methods were analyzed to focus on a clear and well-founded formal description of the integration framework. The IDEF0 modeling method was selected because it has already been used in the context of system engineering and in the context of LCA and, at the same time it focuses on considering information flows (Brundage et al. 2019; Nöcker 2012). ISO 14040 was selected to analyze the functions of the LCA software, as this is the relevant standard for life cycle assessment. The four steps of the LCA form the four functions of the LCA software, each of which the required information was derived separately based on the description within DIN EN ISO 14404 (DIN EN ISO 14040). The market analysis of ERP systems according to HARDJOSUWITO ET AL. and the MES function modules from KLETTI form the basis of a generic description of function modules, which can serve as a source of information (Hardjosuwito et al. 2021; Kletti 2015). The focus was placed on ERP and MES as these are widely used systems in the context of manufacturing companies and to focus on the scope of the analysis.

5. INTEGRATION FRAMEWORK FOR LIFE CYCLE ASSESSMENT

5.1 Formal Description of the Integration Framework

The information-based integration framework is formally described using an adaptation of the IDEF0 methodology. IDEF0 modeling focuses on activities representing functions or processes that convert a defined input into an output (Colquhoun et al. 2007). This paper focuses on functions, which are defined as information transformation processes (Scheer 1998). The formal description of the integration framework is shown in Figure 3.

Input information is transformed into defined output information via the module's functions. Input information originates from systems within the IT landscape or externally (e.g. through user input). Control information has a regulating effect and represents specifications and restrictions of the functions. Output information is created due to the information transformation process and can be used by users or other IT systems. Mechanisms by IDEF0 are not explicitly considered in order to reduce the complexity of the framework. According to IDEF0, functions can be set in hierarchical relationships to combine several functions into one module (Colquhoun et al. 2007). Individual functions are described as analogs by control, input, and output information. The paper aims to integrate a separate LCA software representing a module in this case. In the context of integration, only the information not internally used is relevant for integration. This corresponds to the principle of modularisation (Balzert 2009). The extension of the original IDEF0 modelling to include the sources of the information and the functions of the module that use the respective information enables the direct representation of all integration-relevant elements.

5.2 Integration Framework for Life Cycle Assessment

Based on the formal description, the four components of the framework are described: Functions of the module, control information, input information and output information (see Figure 3). The description of the information for each function is detailed by the adapted description of the IDEF0 framework.

Founded on DIN EN ISO 14040, the Life Cycle Assessment module consists of the following functions: Goal and scope

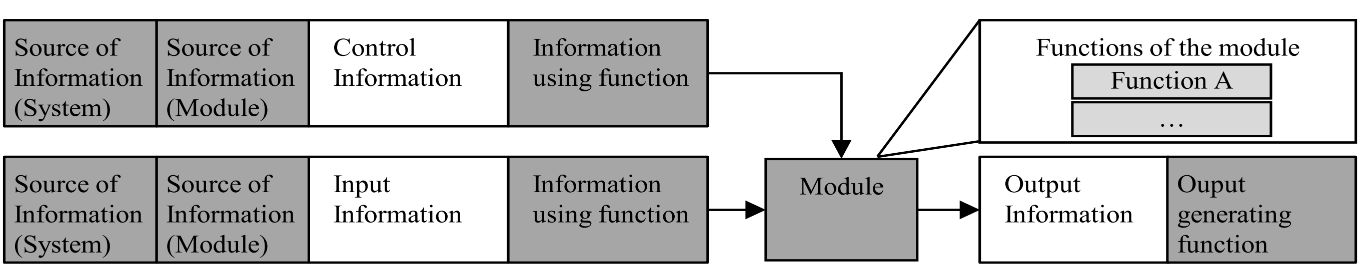

Figure 2 Formal description of the Integration Framework based on IDEF0

definition (A), Inventory analysis (B), Impact assessment (C), and Interpretation (D). The function goal and scope definition (A) formalizes a problem definition based on various control information into a study goal and a defined study scope. The function inventory analysis (B) uses the output information of the study scope as control information to calculate the inventory of all materials and energy flows in the relevant scope. Various input information is required for function B. The output information inventory level from function B is transformed into quantitative impact assessments by function C, considering the scope of the study. The fourth functionality (D) evaluates the impact assessments and generates the ecological footprints and hotspot analyses. This information can be used to derive measures to reduce future environmental impacts, for example if it is determined that specific work steps have a particularly high impact. Please refer to DIN EN ISO 14040 for a more detailed functional description. (DIN EN ISO 14040)

Control information

Control information are decisions and requirements that regulate how the inputs of the respective functions are transformed into outputs. In the context of the LCA module, this is information for the function of goal and scope definition (A). This information is mainly user-based input and therefore from an external source and not from the existing IT landscape. Assumptions and restrictions result from the modeling decisions of the user. Constraints can, for example, be related to assumptions and the choice of method. The evaluation method comprises decisions on how the results of the LCA are to be analyzed. The control information impact assessment method and impact categories contain specifications on which impact categories are considered within the scope of the LCA and which impact assessment method is used. The Cut-Off criteria and allocation method information contain decisions on which flows and processes are not included in the analysis and how environmental impacts are allocated to multiple outputs if a system has multiple outputs. The choice of system boundary determines which processes are included in the analysis. Among other things, it is determined whether a gate-to-gate, cradle-to-gate, or cradle-to-cradle analysis is to be carried out. The control information functional unit determines a clearly definable and definable and measurable reference value. The functional unit must represent the function of the analyzed system and serve as a reference value to which inputs and outputs are related. The Type of report, Type of critical review if provided, and requirements for data quality include the definition of how the results of the LCA are to be documented and prepared. It also determines whether critical review should take place and how it should be organized. In addition, requirements for data quality are also defined. (DIN EN ISO 14040).

Input information

The problem definition represents the motivation for carrying out the LCA. It includes the product system under

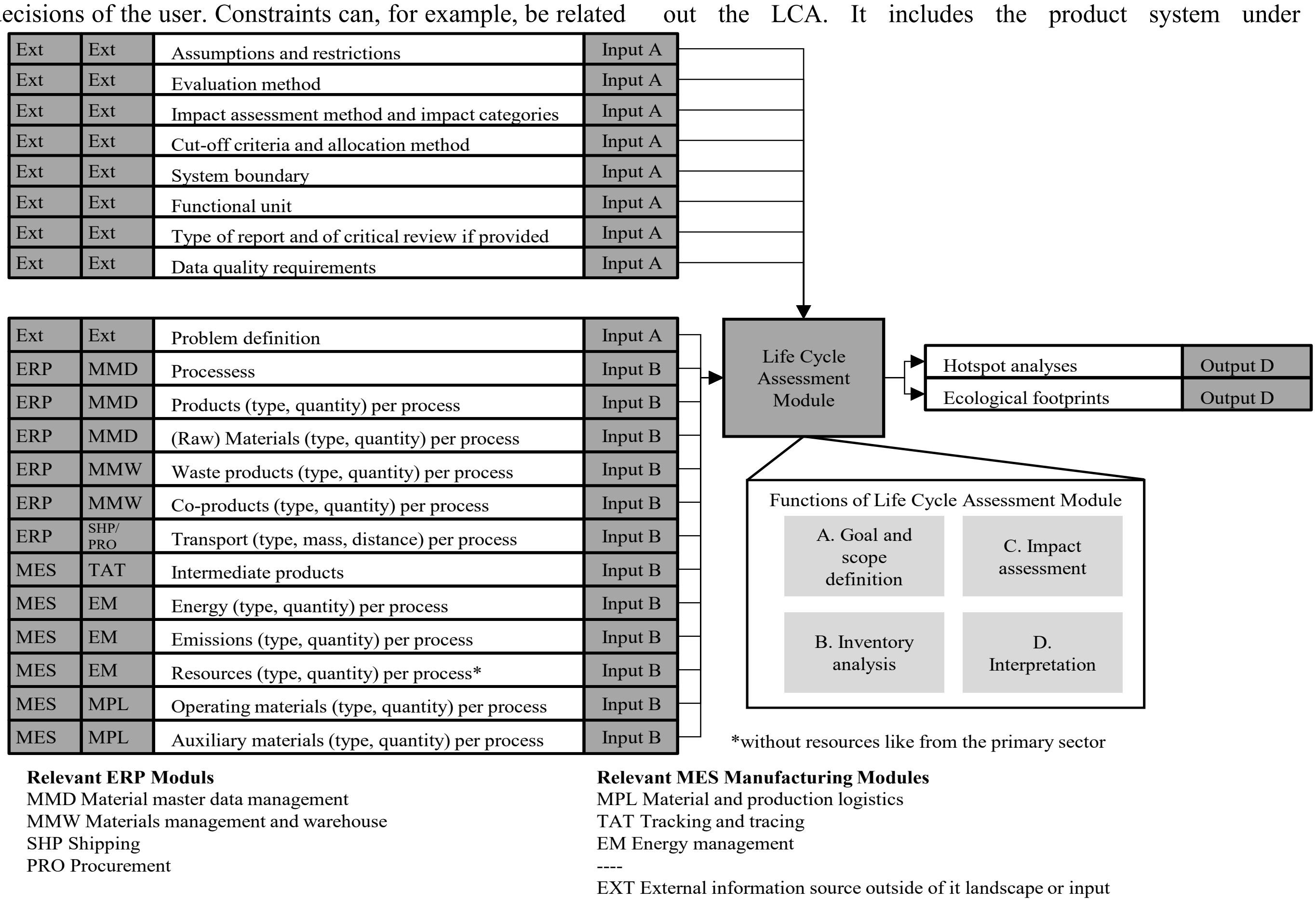

Figure 3 Information-based Integration Framework of Life Cycle Assessment

consideration, the reasons for carrying out an LCA, and the target group of the LCA. This information is converted into a study goal and a defined study scope by function a, considering various control information. (DIN EN ISO 14040) The problem definition is a user-based information input. Further input information is used in function b and can be integrated from the existing IT landscape. The ERP can provide the input information processes, products per process, and material per process or, more precisely, by a material master data management module. This module contains both article and routing-related master data. Process information in the LCA context represents routings, which contains information on operations and work instructions such as necessary times and machines (Wetzchewald 2020). Information on products and (raw) materials can also be found in material master data management. Characteristics such as quantity, mass, and dimensions are stored here both for raw materials in the classic sense and for components. A distinction is also made between in-house and external procurement. If material properties differ depending on the origin, these differences can be mapped as supplier-related material master data. In addition, all sellable products, including their associated bills of materials, are stored within this module. (Hardjosuwito et al. 2021; Külschbach 2021; Kurbel 2021). The information regarding waste products and co-products can also be obtained from the ERP system, or more precisely from the Materials management and warehouse module. The materials management and warehouse module contains functions for monitoring stocks and goods in the production cycle and warehouse. For this purpose, information on warehouse types, locations, and movements is managed. The information on waste and co-products is available here, as this module has functionalities for classifying, defining, and managing any by-products and co-products (Hardjosuwito et al. 2021; Külschbach 2021). In addition, the MES module Material and Production Logistics could also be used, as this supports the control of material in production (Wetzchewald 2020).

Transport information is managed in the shipping module of an ERP system. This module contains all functions related to the dispatch and transport of shipping and transporting products to the customer. Additionally, Information about incoming shipments is related to procurement activities. Procurement-related activities are managed within the ERP module Procurement. (Hardjosuwito et al. 2021). The MES module Tracking and Tracing is the primary source of information for tracking intermediate products, as it can be used to trace produced items across all stages of the process chain (Kletti 2015). Master data on intermediate products is also available from the ERP system's material master data management (Hardjosuwito et al. 2021).

Information on the energy used and the emissions can be integrated from the MES and, more specifically, from an energy management module. Energy information is managed centrally in the energy management module of an ME system. Data acquisition at the production facilities using energy meters and correlations between production processes and energy consumption can be energy consumption. In addition to electrical energy, thermal energy, water, and gas consumption can also be monitored (Kletti 2015). Emissions in the context of LCA are only understood to be those flows into the environment that pass directly from the system boundrey of the company under consideration into the environment. Emissions can be measured depending on the degree of implementation of the energy management module. It should be noted here that, in practice, this is a rare exception. Resources refer to flows that originate directly from the environment. Examples are ores from own mining or water taken directly from bodies of water. As the analysis focuses on manufacturing companies, resources assigned to the first example are not included in the analysis. Information from an energy management module can represent the withdrawal of media, such as water, from the direct environment. Information on operating and auxiliary materials can primarily be provided via the MES material and production logistics module, creating transparency about current circulating stocks (Kletti 2015). Auxiliary materials refer to all materials used to supplement a product's manufacture. Examples include screws, nails, rivets or paint. The reason why they represent a separate category in the context of this paper is that they are treated differently from "raw materials" in companies. Operating materials differ from "raw materials" and "auxiliary materials" in that they are required for production but are not incorporated into the finished product (e.g. lubricants). If required, operating and auxiliary materials consumption can be assigned to the orders via production data acquisition (Kletti 2015). Master data on the operating and auxiliary materials used is stored in material master data management so that additional information from the ERP can be used.

Output information

The described input information is transformed into corresponding output information by the four functions of the LCA, considering the relevant control information. ERP and MES information is used exclusively as a source of information for the LCA function of the inventory analysis. Other input information comes from external input. Output information from the LCA module includes ecological footprints and hotspot analyses. This output is provided by the function interpretation (function D). Ecological footprints can be used to analyze the actual environmental impact of products or activities. Hotspot analyses are used to examine the drivers that significantly influence the environmental impact of products or activities. Both ecological footprints and hotspot analyses provide a basis for decision-making.

6. CONCLUSION AND OUTLOOK

LCA is one of the fundamental methods to facilitate effective decisions in the context of sustainability transformation. However, the current implementation of LCA is inefficient due to detached software applications and manual data imports. Utilizing data from existing information systems offers the potential for a significant increase in efficiency. The integration framework described offers companies a blueprint for the conceptual integration of their specific LCA software, considering the company-specific IT landscape. The blueprint serves as a reference for the company-specific integration of specific LCA software into the IT landscape. This reduces the effort involved in designing the integration. For future research, it is necessary to consider that there is also other sustainability software with similar information demands and functions. To reduce the complexity of IT landscapes, software applications in the context of sustainability should be designed in a modular and adjunctive way. This means that, on the one hand, functions are not duplicated within the IT landscape, but at the same time, there is transparency regarding the flow of information within the IT landscape.

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