Towards Sustainability Modelling with Attribute Dependency Graphs - A Case Study on Industrial Robots

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Abstract: The need to understand the ecological impact of industrial processes is increasing. While compliance with regulations is essential, identifying key influencing attributes remains challenging due to their interconnected and multidisciplinary nature. Lifecycle Assessment (LCA) aids in mapping product-related processes and identifying phases with significant ecological impact but often does not provide actionable design measures. This highlights the necessity for complementary modelling approaches that support the derivation of design insights. In this work, we utilize so-called Attribute Dependency Graphs (ADGs) as a modelling language connecting detailed component-level design with product-level sustainability metrics. Using an industrial robot as a case study, we demonstrate (1) the use of ADGs to bridge sustainability criteria with quantitative design details, (2) a modular approach for modelling multidisciplinary properties, and (3) a practical example of their application in an industrial context.

Keywords: Sustainability, Modelling, Robotics

1 Introduction

Systems modelling emerged as a tool for gaining control over complexity (Hu et al., 2020). Nowadays, complicated systems are made tangible using modelling approaches. This applies to processes on a business level, where the *Business Process Model and Notation (BPMN)* is a common framework, or to engineering procedures, where *Model Based System Engineering (MBSE)* is a state-of-the-art modelling framework. Sustainability is widely recognized as a highly complex challenge (Kirschke & Newig, 2017). Modelling sustainability is essential to systematically identify, assess, and mitigate environmental impacts throughout a product's lifecycle, enabling informed decision-making that promotes sustainable development (Hauschild et al., 2004). By creating sustainability models, organizations can better understand the complex interactions between environmental, economic, and social factors, which is crucial for achieving long-term ecological balance and aligning with global sustainability goals (Knudson, 2023). However, current modelling approaches can become complex and often require specialized expertise to effectively identify the key drivers of sustainability-oriented quantities of interest. This paper introduces Attribute Dependency Graphs (ADG) as an easily accessible method to understand the impact of specific design variables on the quantities of interest. The approach is particularly suitable for the early development stages, when detailed design information is limited. ADGs are a modelling approach for documenting properties and dependencies between them in a particular way: technical consequences of realized technical attributes are distinguished from requirements and design goals to avoid feedback loops. (Rötzer et al., 2022). We propose that ADGs can support environmental analysis. The following sections demonstrate the possibilities of using ADGs in this context in a concrete case study. While this work focuses on environmental sustainability and, furthermore, on carbon emissions, the methodology can also be applied to other sustainability aspects.

2 State of the Art

2.1 Literature review

The literature review is guided by a research plan, shown in Table 1. This plan combines the different core topics of this paper. With the use of 'AND' and 'OR' operators, a search string was created and searched in Scopus; additionally, the keywords sustainability and modelling were selected to narrow down literature in the field of engineering. This resulted in the identification of relevant publications that were then used as the input for the upcoming chapters.

Table 1. Research strategy plan for identifying existing applied use cases of modelling methods in a sustainability context

Context	Method	Domain
Sustainability	Systems Modelling	Product Development
Product Carbon Footprint	Model Based Systems Engineering	Product Design
Carbon Emissions	MBSE	Product Concepts
Lifecycle Analysis	Business Process Modelling Notation	
Lifecycle Assessment	BPMN	
LCA	Systems Engineering	
Product Carbon Footprint	SysML	
PCF	Systems Modelling Language	

2.2 Lifecycle assessment: A detailed view of product sustainability

Lifecycle Assessment (LCA) is a method used to evaluate a product's environmental impact throughout its lifetime. LCAs can be conducted in accordance with various standards or guidelines. (European Environment Agency, 1998) The Greenhouse Gas Protocol provides a framework for systematically accounting for a product's carbon footprint, covering tasks such as scope and boundary setting, data collection, uncertainty assessment, and the calculation of carbon inventory results. Each task is accompanied by a set of requirements that outline the necessary actions for each step of the carbon accounting process. (World Resources Institute, 2011) This demonstrates that an LCA sets the context from the initial definition to the final allocation and calculation of inventory data. However, the framework does not provide specific methods to support each step, thereby creating a need for additional methodologies to describe systems, processes, behaviors, and dependencies. For example, Früchtl et al. (2020) underline this by discussing the use of LCA as a framework for understanding and enhancing sustainability across product lifecycles. Then, the need for more comprehensive and integrated frameworks that combine LCA with interdisciplinary methods is identified. Curran (2014) reinforces this point by identifying persistent challenges in aligning the assessment goal with the modelling approach, as well as the reliability and transparency of underlying assumptions, as limitations in current LCA practice. Various fitting complementary modelling approaches are currently being explored in research; examples of these are discussed in the following chapters.

2.3 Modelling sustainability: The engineering view

The need for fitting lifecycle modelling approaches in an engineering context is present, and toolboxes and modelling frameworks already exist. MBSE is especially known as a helpful framework in this context. MBSE describes the support of system requirements, design, analysis, verification and validation through the formalized use of modelling in different product development and lifecycle phases (Long & Scott, 2011). The modelling front-end of MBSE, called Systems Modelling Language (SysML), consists of several types of models to describe systems regarding their requirements, functions, logic, behavior and structure (Friedenthal, 2014). As an example of using SysML in a sustainability context, Bougain and Gerhard (2017a) suggested first using diagrams at the requirement level to include sustainability-related criteria, as well as measures for solving sustainability problems. They then added lifecycle data such as energy and material consumption into diagrams of specific parts on a structural level to account for them later in diagrams on a parametric level. This procedure offers a foundation for automated sustainability assessments and, therefore, enhanced design decision-making. However, the process requires in-depth knowledge and syntactic understanding of SysML and is focused on the designers of a product, which can hinder adoption and usability when taking various other stakeholders across the value chain into account. Eigner et al. (2014) incorporate sustainability-related data like material and energy consumption as well as emissions into modelling on a structural and parametric level while also integrating the modelling of different use cases and their sustainability-related criteria on an activity level. The traceability capabilities of a procedure like this are highlighted, this enables, for example, regulatory changes on emissions to be broken down into changes on a logical system level. While this enhanced traceability represents a significant strength, the approach lacks a clear mechanism to further visualize and identify the key design variables that influence the quantities of interest. Bougain and Gerhard (2017b) developed two databases: one to handle SysML models and another to manage environmental impact data. In this approach, environmental impacts are mapped onto SysML model elements, enabling environmentally guided decisions within the product development process. This integration supports design engineers in assessing the environmental consequences of design choices and enables the reuse of past eco-design knowledge through a case-based reasoning approach. While this provides designers with the opportunity to implement rapid adjustments based on prior experience, it may also lead to the integration of hidden assumptions and constrain design flexibility. Melzer et al. (2024) propose an approach for developing product families in a sustainable manner by using SysML to model the product architecture and integrating ontologies to map relevant sustainability criteria onto it. While this method enables the efficient assignment of environmental sustainability aspects within a product family, it needs to be extended to incorporate a broader range of sustainability drivers across the entire value chain.

2.4 Modelling sustainability: The business view

Businesses also use a variety of modelling methods that are parallel to modelling procedures in the engineering context. The need arises especially when taking value chain complexities into account. An example framework for this would be the BPMN. As value chain considerations are a crucial part of an LCA, the use of BPMN in this context is already being explored. As an example, Asare et al. (2020) developed a BPMN-based workflow to integrate building information modelling with lifecycle assessment and energy analysis, focusing on sustainable building design in Ghana, Africa. BPMN structures the tasks and interactions, ensuring a transparent, repeatable approach for sustainability assessments throughout building design. The study highlights the need for a formalized, repeatable process to ensure consistent application of the underlying frameworks. While the approach enables informed decision-making in the building industry, it relies on the availability of previously conducted lifecycle assessments and pre-existing environmental datasets. This increases modelling complexity and the effort required to adapt the method to specific project contexts. Gorecki et al. (2020) use BPMN to model and orchestrate smart production systems, integrating simulation tools for improved sustainability tracking. BPMN provides a clear structure for managing interoperability across multiple simulation components, enhancing data flow and task management. The framework's capacity to monitor production metrics (e.g., energy usage or efficiency) enables efficient use for lifecycle assessment. While the framework provides an automated pathway from sustainability modelling to simulation, including automated risk assessments, interactions between individual process instances are not explicitly captured in the modelling phase. This creates a limitation when attempting to analyze dependencies between design variables and quantities of interest. Apart from BPMN, other modelling approaches are being used to incorporate sustainability into enterprises. For example, Dossou (2018) developed a sustainability-centric reference model for small and medium-sized enterprises (SMEs), primarily using the GRAI methodology. The model incorporates social, environmental, and societal dimensions into decision-making and performance evaluation, with a focus on long-term sustainability outcomes. However, to enable more comprehensive sustainability analyses, the approach needs to be expanded to account for the specific sustainability characteristics of individual industrial processes. Ngossaha et al. (2017) incorporate the object-process methodology to assess the sustainability of transportation systems under uncertain conditions. By evaluating economic, environmental, and social impacts, the approach supports lifecycle thinking, helping to identify sustainable transport options despite data uncertainties. However, while the method effectively supports sustainability assessment in transportation policy contexts, it remains domain-specific and would require adaptation to enable broader lifecycle-focused applicability across diverse engineering disciplines.

In comparison to the presented approaches where properties are part of other elements or processes, ADGs are a sole representation of properties and their behavior. Therefore, in contrast to for example, SysML and BPMN enabling a focused view of how sustainability criteria are formed while reducing notational complexity. The following chapters of this paper will explore the advantages of ADGs in sustainability modelling through a case study. To conclude, Table 2 shows the different scenarios where the analyzed modelling methods and ADGs can support an LCA.

Table 2. Comparison of engineering, business modelling approaches and ADGs in the context of an LCA

Method	Application Possibilities in the Context of an LCA
Engineering view (e.g. SysML)	Connecting sustainability requirements of components and functions. Therefore, traceability at multiple product levels is enabled. Integrating strategies for eco-design at a requirement level. Accounting for and assessing different use cases for products regarding eco indicators Enabling automation of LCAs via connecting sustainability-relevant parameters and mathematical models. Supporting information sharing across different lifecycle stages by sharing the same information base. Assisting in the mapping of sustainability requirements to the functional architecture of a product family. Guiding the definition and validation of sustainability key performance indicators and related requirements. (Bougain & Gerhard, 2017a; Bougain & Gerhard, 2017b; Eigner et al., 2014; Melzer et al., 2024)
Business view (e.g. BPMN)	Structuring tasks and interactions to ensure a transparent, repeatable approach for sustainability assessments throughout the development phase. Providing structure for managing interoperability across multiple simulation components, enhancing data flow and task management. Integrating social, environmental, and societal dimensions into decision-making and performance assessments on a process level. Structuring simulation stages that could span across multiple lifecycle phases. (Asare et al., 2020; Gorecki et al., 2020; Ngossaha et al., 2017)
ADGs (engineering or business view)	Documenting the influencing design variables on sustainability, additionally enhancing clarity without the occurrence of circular dependencies. Providing designers with clear and actionable insights to improve sustainability by avoiding circular dependencies. Balancing the level of detail and the notational complexity to ensure understandability. Enabling accessibility to non-engineers and applicability across different domains, ensuring the inclusion of all sustainability improvement potentials. Provide a building plan for requirement decomposition with respect to various quantities of interest while avoiding the occurrence of hidden assumptions (Rötzer et al., 2022; Soika et al., 2024)

3 Methodology

3.1 Attribute Dependency Graphs

ADGs are a tool for modelling the technical dependency between properties of complex systems while avoiding circular dependencies. It consists of a hierarchical structure containing directly controllable design variables that, through the possible creation of intermediate attributes, have an influence on the not directly controllable quantities of interest. Additionally, design parameters represent properties that cannot be influenced. The rule set of ADGs ensures that no hidden assumptions are made. It is essential to distinguish between realized attributes and requirements (Rötzer et al., 2022). Additionally, if the size of an ADG becomes too big that it is not easy to comprehend anymore, this paper introduces property containers that help to zoom into specific areas of an ADG. Figure 2 displays this rule set.

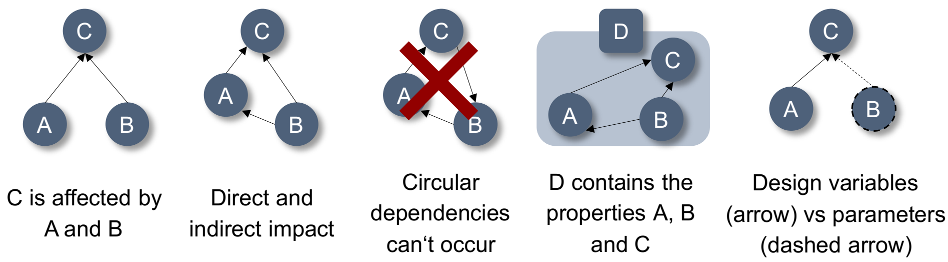


Figure 2. ADG rule set adapted from Rötzer et al. (2022)

3.2 A generic Attribute Dependency Graph for sustainability

To provide a comprehensive understanding of the property allocation influencing sustainability, a generic sustainability ADG is presented in Figure 3. This model comprises various property containers, as defined in the accompanying table, and illustrates their connections to sustainability-related properties or other property containers. The model considers the properties of different product lifecycle phases starting with the material production, which also results in the first environmental impact. Following, the properties of raw material production define the material-associated properties. These, along with component design properties, determine the properties of the production process. The combined attributes of design, production, post-processing, and material properties then define the realized component properties. These component properties connect to the assembled product, as well as to the necessary transportation properties. Finally, the product properties are linked to the use phase. This study will further examine the yellow highlighted property containers of the production phase, the different components, the product and the use phase in the following chapters.

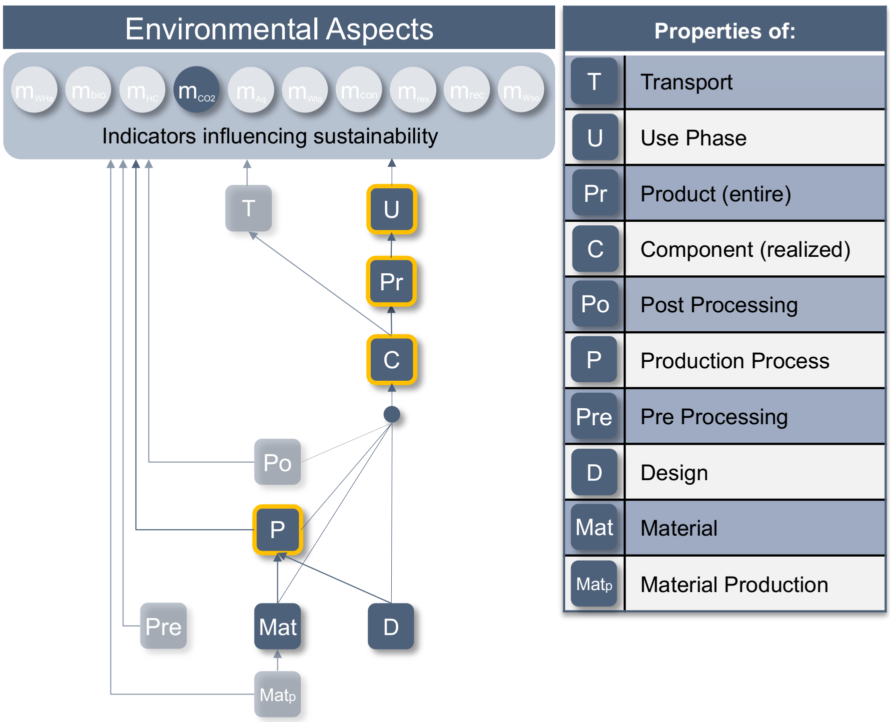


Figure 3. A generic sustainability ADG

4 Academic case study

There has been a steady increase in demand for automation in the manufacturing sector, especially for material handling applications like sorting, pick-and-place, and palletizing. Industrial robots are flexible and are often used to perform such manipulation tasks. Robotic systems were chosen as an example as they are multidisciplinary and offer a sufficiently complex representative use case to highlight the benefits of the current study. Furthermore, this setting includes various lifecycle and production phases, each of which has an individual environmental impact. While there is a general understanding of how the different production methods are connected, the influence of the design variables on the sustainability-related quantities of interest still needs to be explored.

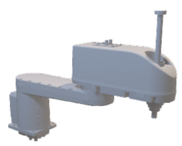
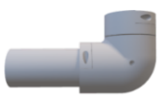
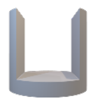
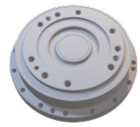
A robotic system consists of several subsystems involving actuation, transmission, controls, sensing and structures. A systematic way to model the different subsystems and their influence on the system-level quantities of interest can, in turn, be represented as an ADG. (Sathuluri et al., 2022). These systems are programmed to perform a necessary task based on the users' requirements. The modelling of each subsystem can be done as a multiscale model describing their time-dependent characteristics and component properties (Ziegler et al., 2023).

5 Results

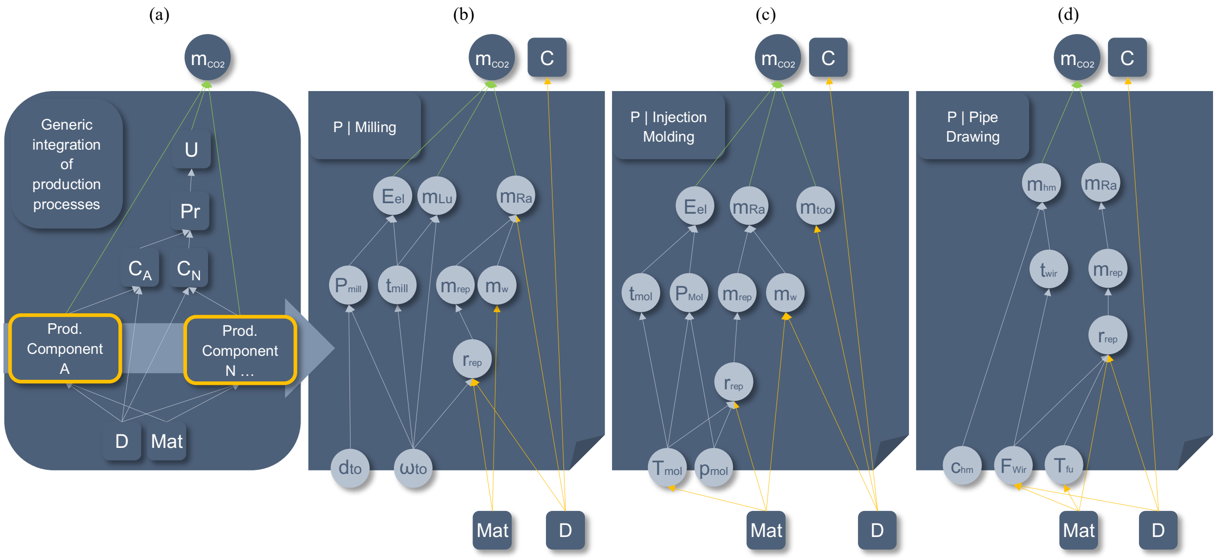
5.2 Module view of the production phase

For the use case of a pick-and-place robot, various components that require production have been identified. These include the joints between robot modules, the gripper, motors, gearboxes, and electronics. In further analysis, electronics will be out of scope. The components and their corresponding production methods are presented in Table 3.

Table 3. Component and production process mapping models from (ABB; CubeMars; Sathuluri et al., 2023; Schaeffler Technologies AG & Co. KG)

		Joints	Grippers	Motors	Gearboxes
	Components				
	Production Processes	Pipe Drawing	Injection Moulding	Casting, Milling	Casting, Milling

The ADGs for the primary production methods of milling, injection moulding, and pipe drawing are shown in Figure 4. They represent modules of the generic sustainability ADG and can now be used to enable sustainability-driven analysis of the production processes. This analysis can focus on a specific procedure or allow for comparison between different procedures. Common attributes, such as rejection rate, waste mass, process duration, and energy consumption, are shared across different procedures and can be the object of overarching improvements, like material or energy source changes. As shown in Figure 4, material properties and component design are included as external properties connected to the production processes. Highlighting the fact that sustainability is influenced by possibly many relevant factors. The production team, for example, can enhance sustainability by improving directly controllable properties, such as angular speed, process pressure, and temperature, which are located at the edge of the ADG as interface variables to the production process. Additionally, properties that the component designer can indirectly influence also become visible. For instance, the rejection rate is affected by attributes of both component design and material properties. When comparing different procedures, process-specific focus points emerge. Examples include the impact of tooling on emissions in injection moulding and the relationship between the choice of heating medium and emissions in pipe drawing.

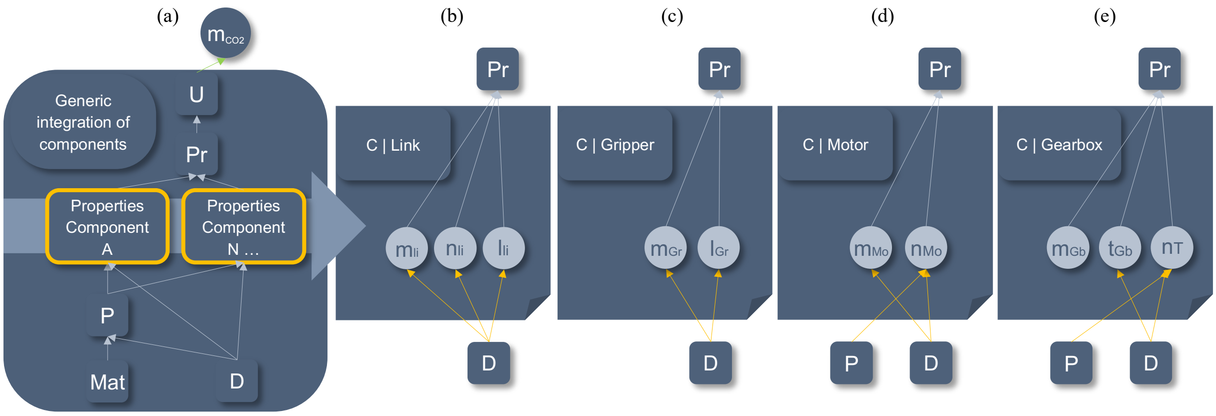


Properties of the Production Processes					
m_{Lu}	Mass Lubricants	m_{Ra}	Mass Raw Material	E_{el}	Electrical Energy
m_{too}	Mass Tooling	m_{hm}	Mass Heat Medium	P_{mill}	Power Consumption Milling
t_{mill}	Time Milling	m_{rep}	Mass Rejected Parts	m_w	Mass Waste Material
t_{mol}	Time Injection Molding	P_{Mol}	Power Consumption Molding	t_{wir}	Time pipe Drawing
r_{rep}	Rate of Rejected Parts	d_{to}	Tool Diameter	ω_{to}	Angular Speed Tool
T_{mol}	Temperature Molding	p_{mol}	Pressure Molding	C_{hm}	Calorific Value Medium
F_{Wir}	Force Pipe Drawing	T_{fu}	Temperature Pipe Drawing		

Figure 4. ADGs of production procedures (a) generic production integration (b) milling (c) injection moulding (d) pipe drawing

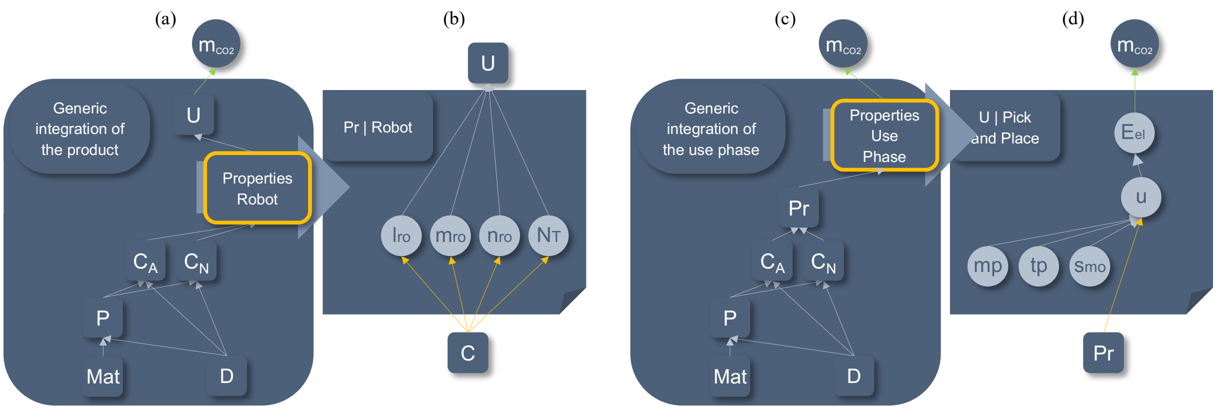
5.3 Module view of the use phase

After the production procedures, the different component ADGs and their interfaces are modelled in Figure 5. Then, the connection between the components and the product, as well as the connection between the use phase and carbon emissions, are modelled in Figure 6. The ADGs illustrate trivial relationships, such as the individual component masses combining to form the total robot mass and the individual component lengths contributing to the overall reach of the robot. Furthermore, the mass and length-related properties are set in context with more component-specific properties like the gear ratio of the gearbox. Furthermore, it is represented that the combined selection of the motor and gearbox determines the product's efficiency, which, in turn, affects the energy consumption during the use phase. In addition to the impact of robot design on emissions, the connections between task properties such as payload mass, task duration, and task distance become evident. This reveals how improvements in the way the robot is utilized can also enhance its sustainability impact.



Properties of the Components					
m_{li}	Mass Link	n_{li}	Amount of Links	l_{li}	Length of Links
m_{Gr}	Mass Gripper	l_{Gr}	Length of Gripper	m_{Mo}	Mass of Motor
n_{Mo}	Efficiency of Motor	m_{Gb}	Mass Gearbox	n_T	Efficiency of Gearbox
t_{Gb}	Gear Ratio				

Figure 5. ADGs of components (a) generic component integration, (b) link, (c) gripper, (d) motor and (e) gearbox



Properties of the Product and Use Phase,					
n_{ro}	Efficiency Robot	l_{ro}	Length Robot	m_{ro}	Mass Robot
mp	Mass Payload	N_T	Transmissions Rate	s_{mo}	Movement Distance
u	Task Performance	tp	Movement Time	E_{el}	Electrical Energy

Figure 6. ADGs of components (a) generic product integration, (b) product, (c) generic use phase integration and (d) use phase

6 Discussion

The presented ADGs document the factors influencing carbon emissions across the various considered perspectives. Compared to other approaches, ADGs offer a simple way to identify the key properties influencing quantities of interest, while remaining easy to communicate across all levels of an organization. The method itself does not provide a quantitative assessment of the individual impact of each factor. However, it defines the interfaces of quantitative models. For future product sustainability improvements, the quantification of the properties will be explored. The use of ADGs is especially effective in the early phases of product development. Since ADGs do not allow circular dependencies, integrating causal relationships based on implicit assumptions that accumulate over the different development stages is challenging. To address this, additional textual documentation could accompany the ADGs, specifying excluded interrelationships, although this may compromise the simplicity that ADGs aim to provide. As ADGs represent properties and their interactions graphically, they are not supposed to replace modelling toolboxes such as SysML, referenced in this study, which contain a multitude of modelling methods and tools. However, they could be integrated into existing approaches or provide a simpler standalone procedure. In particular, ADGs can serve as an abstraction layer within SysML-based modelling by identifying key influencing properties that inform requirement and parametric diagrams. Likewise, ADG outputs can complement BPMN by linking property-level sustainability insights to specific business processes, enabling a structured yet accessible integration of environmental criteria into lifecycle-oriented workflows. As a standalone modelling approach, ADGs offer the opportunity to support lifecycle assessments by systematically linking design variables to sustainability-relevant properties across all lifecycle stages. This includes the ability to model material sourcing and production by linking material properties, sourcing decisions, and processing parameters to environmental impacts. Furthermore, end-of-life aspects such as recycling, remanufacturing, and reuse can be incorporated into the ADG structure through properties like disassemblability, material separability, or component reusability, enabling early identification of design choices that align with circular economy goals and the 9R principles.

7 Conclusion

The proposed use of ADGs in modelling sustainability-related criteria was shown to have various advantages, (1) it is a very simple procedure to gain insights on only the essential, context-related property behavior and, therefore, focuses reporting and improvement steps on only the necessary influences. (2) This, combined with the low notational complexity, makes the modelling approach accessible and easily comprehensible by various stakeholders across a company or even the entire value chain. (3) It enables a comprehensive understanding of where and by whom sustainable impact can be influenced. (4) Thus, it serves as a tool not only for engineers but also for a broader group of stakeholders, which is particularly important in sustainability modelling, where impacts can arise in every phase and step of the lifecycle and value chain. A generic sustainability ADG containing property containers was introduced to be applied in any kind of lifecycle assessment. This generic model was then filled in the case study with example ADGs of the production and use phase for a pick and place robot. This highlighted the potential of using ADGs within lifecycle assessment, where the method can support activities beginning with goal and scope definition by clarifying quantities of interest and setting the boundaries of consideration. Furthermore, as noted, the focus on identifying sustainability-influencing properties and their behavior aids in the inventory phase of an LCA and contributes to further sustainability-oriented improvements.

8 Outlook

Since ADGs are represented primarily by connections between properties, further research could explore methods for automating the ADG creation process. An action to support this is the precreation of sustainability ADGs regarding common production processes, products, and use phases in case of reusing them in future projects. Another aspect to be further elaborated is the automated transfer of an ADG into the lifecycle assessment, as the proposed sustainability-orientated ADGs already contain the driving properties for LCA, these can already be copied into the reporting framework, where they then would need to be post-processed by adding further variables for the inventory calculation. Finally, the modelling language of ADGs and design structure matrices are compatible with respect to their description of the connections between attributes and the quantities of interest. Future work shall focus on the interoperability of these frameworks.

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