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Assessing and Visualising Sustainability Value of Product Concepts in Early Design Stage for Strategic Decision Making

Sze Yin Kwok[a,*], Sophie Isaksson Hallstedt[a,b], Johanna Wallin Nylander[c]

[a]*Department of Strategic Sustainable Development, Blekinge Institute of Technology, SE-371 79 Karlskrona, Sweden*
[b]*Department of Industrial and Materials Science, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden*
[c]*GKN Aerospace Engine, Trollhätan, Sweden*

* Corresponding author. Tel.:+46 (0) 455-385503; *E-mail address:* sze.yin.kwok@bth.se

Abstract

Integrating sustainability into early product design stage is crucial for companies to navigate complexity effectively. Based on a long-term research collaboration with an aerospace product manufacturer, this paper introduces an improved prototype of the Sustainability Criteria and Product Life-Cycle Data Simulation digital decision-support tool for visualising and comparing the sustainability implications of product design concepts. Unlike existing tools, it allows quantitative comparisons in early design stages and is based on overarching socio-ecological sustainability principles and a backcasting perspective. A sustainability merit score for each product design concept is derived from selected indicators and sustainability criteria. The paper also reports on the results from a focus group evaluation study and discusses the value and challenges faced when developing this type of tool, including accuracy, data availability limitations, and the dilemma of indicator weighting.

Keywords: industrial case; sustainable design; decision support tool; sustainability indicators; early design stage

1. Introduction and background

To develop more sustainable solutions, it is necessary to have efficient support tools, processes, increased capabilities in the design team and lifecycle engineers [1]. The trend analysis proposed by Isaksson and Eckert [2] also anticipates that advancement in simulation technology and artificial intelligence will be useful for designing the desired behaviours of systems/products, since digitalisation will permeate many aspects of our lives. This will demand contemporary decision support that can quantify, simulate, predict, visualize and monetise sustainability impact of products, and guide the designing of circular options in a time efficient manner. In response to the opportunities, product developers should change their mindsets and shift their focus to sustainability-impact-based product requirements instead of focusing on performance-based product requirements as of nowadays [3]. However, integrating sustainability in early product development faces several challenges: (i) a vast number of support tools and methods for sustainable design exist but their use is limited [4]; (ii) a strategic perspective is often lacking [5]; (iii) a systems perspective is a prerequisite for effective work with sustainable product development [6], for instance to avoid sub-optimisation, and organizations need support on this [7]; (iv) interdependencies between different sustainability aspects and between sustainability aspects and other parameters create difficult trade-offs [8]; and (v) the qualitative nature of sustainability complicates quantification. Other challenges include time and data availability in early stages of engineering design to analyse sustainability in a rigorous manner without compromising the completeness of sustainability or the product life-cycle perspective.

To improve adoption of sustainable design tools in industry, Ahmad et al. [9] suggest to improve the maturity level of support tools and to meet the desired characteristics, which

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means developing tools that are easy to use, adaptable to different situations, and yield results that are easy to understand and communicate [10]. Another suggested focus is the adoption of sustainable product development (SPD) tools for computer-based systems to increase their usability in industries [11] to address industry needs and value [12].

This research aims to contribute to the Sustainable Design field by answering the research questions: *"How to develop a decision support tool that can quantitatively assess the sustainability performance of product design concepts in early design stage in connection to the product engineering characteristics?"*, and *"What are the value and challenges of this type of decision support tool that assess sustainability performance of product concepts in early design stage when time and data availability is limited?"* This paper reports on the iterative design and development of a novel decision-support approach called Sustainability Criteria And product life cycle Data Simulation (SCADS) that visualises strategic sustainability implications of different product concepts and allows comparison of their sustainability performance in early product innovation phase. The background to this work, a description of the SCADS approach and the first prototype and the initial evaluation are published in a conference paper [13]. This paper presents the second version of the prototype digital tool and the results from a focus group study.

2. Research methods

This paper focuses on the results from a prescriptive study and a related evaluation study, where the increased knowledge based on the development and evaluation of the previous prototype [13], was used to inform the design of the new prototype (the second prototype) of the SCADS digital tool. The prototype was developed based on industrial cases with real data. The case company was an aerospace engine component manufacturer in Sweden. Bi-weekly co-creation meetings were conducted with the case company over a one-year period. Each meeting lasted for 1 to 2 hours. During these meetings, the partner company's sustainability engineer provided information and feedback related to the sustainability indicators, calculation approach of these indicators, data about product concepts of the company, visualisation methods of the digital tool and challenges faced by the company and opportunities brought by this proposed tool. The second prototype of the digital tool was developed based on the data collected from these discussions.

To evaluate the prototype, a focus group study was conducted with seven people, including four academic researchers from the field of sustainable product development and three industrial researchers from the case company who specialised in sustainability and product development. The focus group took place in a 4-hour workshop during which various tools for assessing sustainability performance during early product development stage, including SCADS, were introduced in detail. The focus group discussion was 1 hour long and involved discussions about the value, limitations of the tool and the challenges faced in its development and usage.

3. A new prototype of SCADS digital tool

The product concepts, jet engine component, of the case company were considered and selected for this stage of prototype development. The second prototype was created using data about three real product concept solutions with fully defined engineering characteristics. These product concepts are alternative designs of a similar product that differ in terms of manufacturing processes, structure, number of components and weight. One of the product concepts existed in the market, one product concept was an experimental product using new manufacturing technologies, and another one was an imaginary incremental product that aligned with the company's vision for sustainability. These products look highly similar in its final form, but they vary in terms of number of components, the one with the least number of components is made of 13 components, the maximum number of components was 19.

The second prototype was developed in *Excel* and contained 17 spreadsheets. The following figures show the screenshots of the first 3 spreadsheets in the file that represented i) the input model (Fig 1), ii) the list of sustainability criteria and sustainability indicators and associated weighting (Fig 2), and iii) the spreadsheet that linked the input data (engineering characteristics of the product concepts) and the sustainability indicators and displayed the results (sustainability merit scores of the product concepts) (Fig 3). These 3 spreadsheets contained the functions for reading user input, linking the sustainability indicators to product engineering characteristics, calculating and displaying the resulting sustainability merit scores of the design concepts. The other 14 spreadsheets included the calculation approach and related databases for the sustainability indicators. Each sustainability indicator was investigated with the aim to define the calculation approach and identify necessary data for determining the value of the indicator. The discussions among the researchers and the company partners explored the contextual meaning of the indicators, deepened the understanding of the manufacturing scenarios in the company, the information needed for producing indicative values, the data available from the case company or other sources, the methods to find missing information/ data, and the methodological and practical challenges faced during the search for information. The co-creation meetings with the case company informed the suggestion of adding 2 new sustainability indicators, making a total of 17 sustainability indicators in the second prototype. Table 1 shows the complete list of 17 leading sustainability criteria, sustainability indicators and related calculation approaches used in the second protype of SCADS digital tool. Table 2 compares the differences of the two prototypes. The second prototype differed from the first prototype, as it:

- allowed multiple components for product concepts;
- allowed the use of different material for different components;
- allowed entry about different manufacturing processes for different components;
- was based on real company data for all indicators, with limitations and assumptions;
- contained 17 sustainability indicators that are fully operationalised.

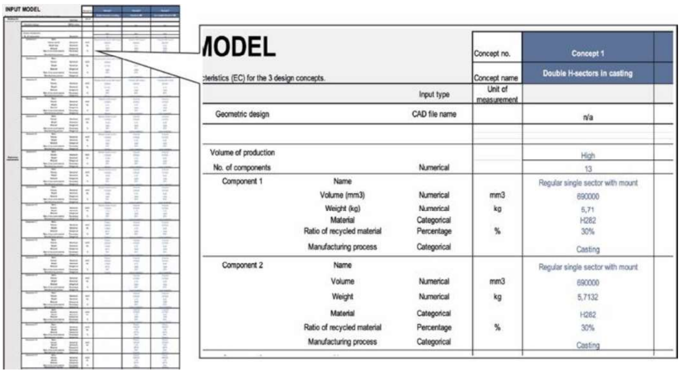

Fig.1. Screenshot of the SCADS digital tool – the input model that reads the product engineering characteristics

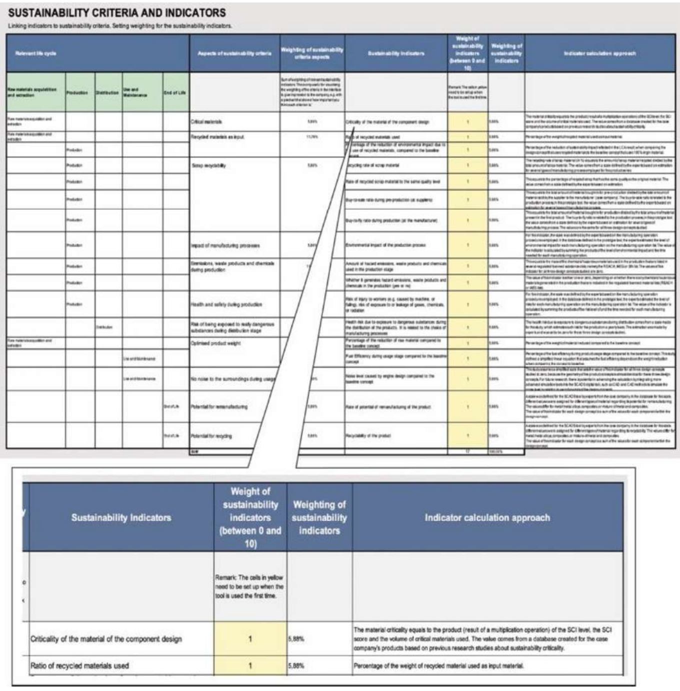

Fig.2. Screenshot of the SCADS digital tool – the list of sustainability criteria and sustainability indicators and associated weighting for calculating the sustainability merit scores

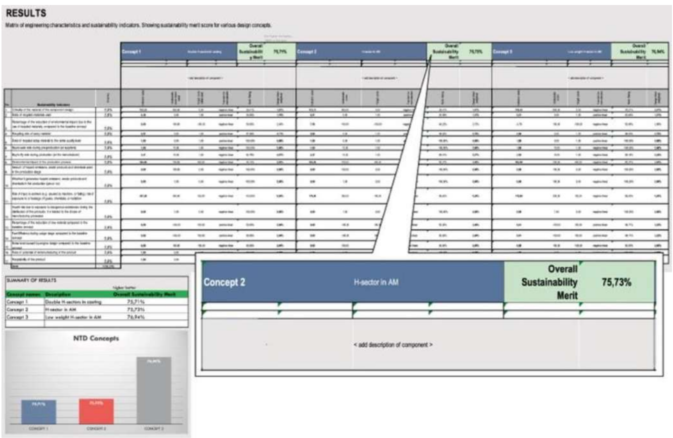

Fig.3. Screenshot of the SCADS digital tool – the page that computes and displays the results

Table 1. List of leading sustainability criteria, sustainability indicators and related calculation approach used in the 2nd protype of SCADS digital tool

Sustainability criteria	**Sustainability indicators**	**Indicator calculation approach**
Avoid critical materials	Criticality of the material of the component design	The material criticality equals to the product (result of a multiplication operation) of the SCI level, the SCI score and the volume of critical materials used. The value comes from a database created for the case company's products based on previous research studies about sustainability criticality (Hallstedt, 2017).
Use recycled materials as input	Ratio of recycled materials used	Percentage of the weight of recycled material used as input material.
	Percentage of the reduction of environmental impact due to the use of recycled materials	Percentage of the reduction of sustainability impact reflected in the LCA result, when comparing the design concept that uses recycled materials to the baseline concept that uses 100% virgin material.
Scrap recyclability	Recycling rate of scrap material	The recycling rate of scrap material (in %) equals to the amount of scrap material recycled divided by the total amount of scrap material. The value comes from a scale defined by the experts based on estimation for several types of manufacturing process employed for this product series.
	Rate of recycled scrap material to the same quality level	This equals to the percentage of recycled scrap that has the same quality as the original material. The value comes from a scale defined by the experts based on estimation.
	Buy-to-sale ratio during pre-production (at suppliers)	This equals to the total amount of material bought in for pre-production divided by the total amount of material sold by the supplier to the manufacturer (case company). The buy-to-sale ratio is related to the production process, in this prototype tool, the value comes from a scale defined by the experts based on estimation for several types of manufacturing process.
	Buy-to-fly ratio during production (at the manufacturer)	This equals to the total amount of material bought in for production divided by the total amount of material present in the final product. The buy-to-fly ratio is related to the production process, the value comes from a scale defined by the experts based on estimation for several types of manufacturing process. The values are the same for all three design concepts studied.
Impact of manufacturing processes	Environmental impact of the production process	The scale was defined by the experts based on the manufacturing operation procedures employed. In the database defined in the prototype tool, the experts estimated the level of environmental impact for each manufacturing operation on the manufacturing operation list. The value of the indicator is calculated by summing the products of the level of environmental impact and the time needed for each manufacturing operation.

Emissions, waste products and chemicals during production	Amount of hazard emissions, waste products and chemicals used in production	This equals to the mass of the chemicals/ hazardous materials used in the production that are listed in several regulated/ banned substances lists, namely the REACH, IAEG or SIN list. The values of this indicator for all three design concepts studied are zero.
	Whether it generates hazard emissions, waste products and chemicals in the production	The value of this indicator is either one or zero, depending on if there is any chemicals/ hazardous materials generated in the production with reference to the regulated/ banned material lists (REACH or IAEG).
Health and safety during production	Risk of injury to workers, risk of exposure to or leakage of gases, chemicals, or radiation	The scale was defined by the experts based on the manufacturing operation procedures. In the database defined in the prototype tool, the experts estimated the level of risks for each manufacturing operation on the manufacturing operation list. The value of the indicator is calculated by summing the products of the risk level of and the time needed for each manufacturing operation.
Risk of being exposed to dangerous substances during distribution	Health risk due to exposure to dangerous substances during the distribution of the products	The health risk due to exposure to dangerous substances during distribution comes from a scale made for this study, which estimates such risk for the product on a yearly basis. The estimation was made by experts and was set to be zero for these three design concepts studied.
Optimised product weight	Percentage of the reduction of raw material	Percentage of the weight of material reduced compared to the baseline concept.
	Fuel Efficiency during usage stage compared to the baseline concept	Percentage of the fuel efficiency during product usage stage compared to the baseline concept. This study defined a simplified linear equation that assumes the fuel efficiency depends on the weight reduction.
No noise to the surroundings during usage	Noise level caused by engine design compared to the baseline concept	This study assumes a simplified scale that sets the value of this indicator for all 3 design concepts studied to zero, as the geometry of the concepts is almost identical for these 3 concepts. For future research, there is potential in advancing the calculation by integrating more advanced simulation tools into the SCADS digital tool, such as CAD and CAE methods to simulate the noise level in relation to aerodynamics of the design concepts.
Potential for remanufacturing	Rate of potential of remanufacturing of the product	A scale was defined for SCADS by experts from the case company. In the database for this scale, different values were assigned for different types of material regarding its potential for remanufacturing. The values differ for metal/ metal alloys, composites, or mixture of metal and composites. The value of this indicator for each design concept is a sum of the values for each component within the design concept.
Potential for recycling	Recyclability of the product	A scale was defined by experts. In the database for this scale, different values were assigned for different types of material regarding its recyclability. The values differ for metal/ metal alloys, composites, or mixture of metal and composites. The value of this indicator for each design concept is a sum of the values for each component within the design concept.

Table 2. Comparing the two prototypes of the SCADS digital tool

	First prototype of the SCADS digital tool	**Second prototype of the SCADS digital tool**
Number of components	This digital tool was useful for assessing single-component product.	This digital tool was useful for assessing both single-component and multiple-component products.
Number of material types	This digital tool allowed one type of material per product.	This digital tool allowed one type of materials per component, the product could be made of many components.
Number of sustainability criteria	11	11
Number of sustainability indicators	15	17
Sustainability indicators calculation	Only a few indicators were operationalised.	All indicators were operationalised with calculation equations defined in Excel.
Ratio of recycled materials used	This information did not exist in the input model.	This information was required in the input model.
Manufacturing process and operations	This information was not used in the ustainability indicators that were operationalised.	Information about manufacturing process and operations were required for the input model. This information was used for calculating the values for multiple sustainability indicators.
Weight	Weight of the product was required as input data.	Weight of the product was calculated by summing the weights of components. The weight of components were calculated based on the volume and material properties of the component.
Volume	There was no information about volume in the input model.	In the input model, this information was required for every component that formed the product.

4. Results and discussions – value of the SCADS tool and challenges faced during development

4.1. Accuracy of the calculation approach

The participants discussed their views about the accuracy of the output of SCADS, including its strengths and weaknesses. In overall, they thought positively about the accuracy of the results presented by SCADS. The tool was considered to be comprehensive, and it covered many sustainability aspects that no other tools did, the comprehensiveness was considered to have a positive effect on the accuracy of the sustainability merit score presented by SCADS. However, since numerous assumptions were made when defining the calculation approach of the indicators, the accuracy of the resulting sustainability scores was limited. The participants understood that the resulting sustainability merit scores, although were numerical scores that concluded the overall sustainability performance of the product design concepts, should not be seen as absolute values. Instead, the scores would be more useful when interpreted as values that enable comparison of different design concepts within the same company or product series. As the assumptions made for these different design concepts would be the same, the SCADS was considered reliable in the sense that the trends visualised would be consistent. For example, if the weighting of the indicators were changed, the absolute values of the sustainability merit scores for various design concepts would change accordingly, but the relative comparison of these design concepts would remain constant, the best design concept with the highest score would always be displayed as the best design concept. Fig 4 illustrates an example comparison of how the final sustainability merit scores for the design concepts might differ when the weighting of the sustainability indicators are set differently. The two spiderweb diagrams on the top row show the merit scores for each sustainability indicator without considering weighting of the indicators, i.e. all the indicators weigh the same and these two diagrams look the same. The spiderweb diagrams in the middle row show the merit scores for each sustainability indicator, on the left the sustainability indicators were equally weighted with a weight of 1 for each indicator, on the right the weight of the first sustainability indicator about material criticality was changed to 3 while the rest of the indicators still have the same weights of 1. The bottom row shows the summary of the results of three design concepts. The overall sustainability merit scores for the design concepts were shown to be different because the weighting used were different.

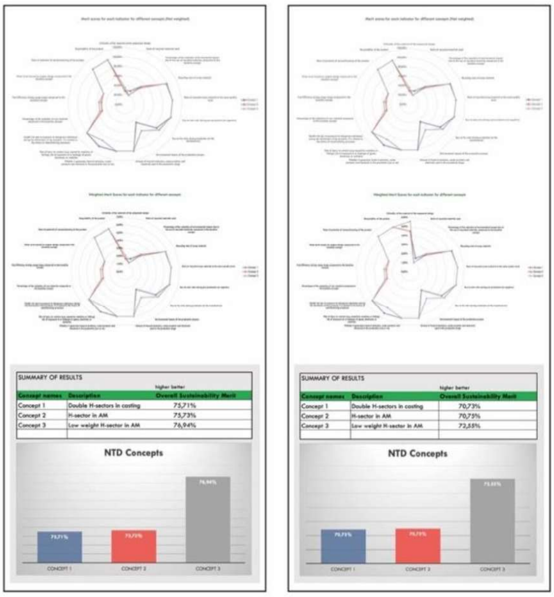

Fig. 4. Screenshot of the SCADS digital tool – comparison of the results when the weighting of the indicators was changed

The accuracy of the results was limited by data availability which would affect the feasibility and practicality in defining the calculation approach of the sustainability indicators. As expressed by the participants, in today's industry practice, experts in the companies have much valuable internal knowledge that are not documented, as a remedy for the lack of measured data, estimations or assumptions were needed when defining the database of the indicators. The knowledge of the companies, for example about the product manufacturing processes and materials, can support the understanding of the sustainability performance of the company and their products, but this knowledge was usually not utilised. To meet the challenges of data availability, the participants suggested to provide guidance to the companies in collecting data for sustainability assessment. They thought that it was important to have an awareness of the risk of sub-optimisation, so that the choice of sustainability indicators and calculation approach were not merely defined based on convenience, but based on a scientific method. It means that companies should not omit certain sustainability indicators simply because the related data was not readily available. The structure and indicators hinted by SCADS can be used as a means to push the boundary and encourage exploration into underdeveloped areas of sustainability assessment. It was agreed that other existing tools, such as material libraries with LCA data, can be connected to SCADS and be utilised for increasing the accuracy of the results. New methods may be needed for related data collection and sustainability assessment.

4.2. Dilemma in weighting different sustainability indicators

The output of SCADS, i.e. the sustainability merit scores of the product design concepts, depended not only on the values of the sustainability indicators but also the weighting of these indicators. The weight of each indicator needed to be set up before the SCADS tool could be used, these relative weights determined the significance of each indicator and reflected the company's priorities.

When discussed how to decide the weighting of the indicators, various possible approaches were mentioned. Some said that the weight of the indicators could be set according to the company's strategies, for example if the company was more concerned about carbon emissions, material reduction or social sustainability, higher weights could be assigned to the indicators related to these aspects. Another opinion was to decide the weights based on scientific methods and unbiased research findings, or to bring in experts from various domains for an agreed set of weighted sustainability indicators. The Sustainability Design Space method and the internal company specific concept selection matrices could provide a means in prioritising relevant sustainability criteria, and can be further expanded to support the definition of indicator weighting. The participants suggested that another way to provide inputs for setting the indicator weighting can be connecting to other value factors on a higher level, for example legislation factors or marketing strategies. It was agreed that the weighting method needs to be transparent and clearly communicated to the user of the SCADS tool, because understanding of the weighting method is very important for the interpretation of the results, trustworthiness of the tool and usefulness of SCADS as a decision support tool. In particular, the users need to be aware of potential trade-offs when balancing different aspects.

4.3. Value of the SCADS digital tool

The participants thought that the SCADS approach and digital tool was valuable for decision making related to design concepts comparison and selection in the context of sustainable product development. They expressed that it was good to be able to assess and visualise sustainability performance of product concepts in early design stage. It was good that SCADS covered a wide range of relevant sustainability indicators specifically customised for the case company, and that it could provide a quick calculation of product sustainability performance in relation to its engineering characteristics. They discussed that it is important not to judge merely based on the absolute values of the final numerical results, but that the user and decision makers should understand how the scores were calculated. Such an understanding would inform decision making based on the values, trend or directions shown in SCADS. For instance, the decision maker may choose a design concept because it has the highest sustainability merit score in SCADS, or in another scenario, if all the design concepts appear to be similar in terms of sustainability performance, the decision maker may then use in this information and make decisions based on other factors or values, e.g. costs, reliability.

The participants pointed out that the factors or sustainability criteria covered in SCADS are independent of each other. The tool can be useful for supporting decision making related to trade-offs, but the user needs to have a good understanding of the methodology behind. They said that it would be interesting to further explore how to connect the sustainability indicators to other design values or higher-level objectives. A challenge faced by the company when using the SCADS tool is related to the trustworthiness of the tool, but not straightforward to address the issues. Another challenge faced by company is how to effectively communicate the meaning of the sustainability merit scores to their customer and earn their trust in the results.

5. Concluding discussions

It is important to increase the capabilities in companies to deal with the complexity to integrate sustainability in early product design stage. This paper presents a new prototype of the Sustainability Criteria And product life-cycle Data Simulation (SCADS) digital tool that was designed based on the lessons learnt when evaluating the first prototype (Kwok et al., 2020). A focus group study was conducted to evaluate the new prototype. The results suggested that the SCADS digital tool can provide positive value for decision making in early product development stage, as it can support concept comparison and selection for sustainable product design. A unique feature of the SCADS tool was that the sustainability indicators were identified using a strategic approach and were customised for the company and their products, with consideration of both short-term and long-term perspectives. The SCADS digital tool generates a numeric sustainability merit score as output for the product design concept, which can be considered as good reference for decision making. However, the sustainability merit scores should not be seen as an indication of absolute sustainability value, but a guidance for decision. The tool was designed to be applicable across various industries for a wide range of products.

The trustworthiness and external validity of the findings are limited since it was an industrial case study with one company. However, due to the aim and scope of this study, acquiring rich and detailed insights with high internal validity was highly important for the prescriptive studies and the abductive process of the prototype development. The paper has not discussed much about how to decide the weights of the indicators. It will be an interesting topic for future research. A deeper understanding of external factors can contribute to refinement of the weighting method of the tool, so that the sustainability merit scores align with customer and other stakeholders' values. For instance, customer preference for sustainable product features and business risk-value perspectives can be considered when setting the weights of sustainability indicators [14, 15].

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