



HAL
open science

Approach Towards Sustainability Modelling and Sustainability Risk Assessment in Manufacturing Systems

Daniel Schneider, Susanne Vernim, Thomas Enck, Gunther Reinhart

► To cite this version:

Daniel Schneider, Susanne Vernim, Thomas Enck, Gunther Reinhart. Approach Towards Sustainability Modelling and Sustainability Risk Assessment in Manufacturing Systems. IFIP International Conference on Advances in Production Management Systems (APMS), Sep 2022, Gyeongju, South Korea. pp.440-447, <10.1007/978-3-031-16407-1_52>. <hal-05386094>

HAL Id: hal-05386094

<https://inria.hal.science/hal-05386094v1>

Submitted on 27 Nov 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License



This document is the original author manuscript of a paper submitted to an IFIP conference proceedings or other IFIP publication by Springer Nature. As such, there may be some differences in the official published version of the paper. Such differences, if any, are usually due to reformatting during preparation for publication or minor corrections made by the author(s) during final proofreading of the publication manuscript.



Approach Towards Sustainability Modelling and Sustainability Risk Assessment in Manufacturing Systems

Daniel Schneider¹ (✉) , Susanne Vernim¹ , Thomas Enck², and Gunther Reinhart¹

¹ Institute for Machine Tools and Industrial Management, Technical University of Munich (TUM), Boltzmannstraße 15, 85748 Garching bei München, Germany
daniel.schneider@iwb.tum.de

² Commerzbank AG, Kaiserplatz, 60311 Frankfurt am Main, Germany

Abstract. Changing environmental conditions and socio-political expectations progressively pose challenges and risks for manufacturing companies in the European Union. These so-called sustainability risks are becoming increasingly important and pose challenges for both the manufacturing and financial industries. While research on sustainability assessment in production is, in principle, already quite advanced, the concept of sustainability risk has so far been discussed mainly without dedicated reference to production and its systems. Based on a brief presentation of the state of the art, this paper, therefore, presents a research concept for modelling the sustainability of production systems to identify and assess sustainability risks. The approach is divided into three steps and covers the phases of sustainability modelling, data extraction, and employment as a risk management tool. Several research aspects to be considered in the context of this concept development are presented. In conclusion, an outlook on how the proposed approach will be employed in the manufacturing and financial industries is given.

Keywords: Sustainability assessment · Sustainability modelling · Sustainability risk · Manufacturing systems · Resilience

1 Introduction

The greenhouse effect is at the centre of current environmental and political debates, resulting from the excessive consumption of fossil fuels and raw materials. An anthropogenic origin of global warming is now assumed to be certain [1], as is the hypothesis that an intensification of climate change would result in massive economic damage [2]. Sustainability or sustainable development was initially defined as the “development which meets the needs of current generations without compromising the ability of future generations to meet their own needs” [3]. It is usually operationalised through the triple bottom line (TBL), a concept pioneered by Elkington [4] that simultaneously considers economic, environmental, and social issues from a microeconomic perspective. A

particularly relevant group of actors pursuing this sustainable development is manufacturing companies. Consequently, there is growing socio-political pressure – especially in the European Union – for sustainable economic activity (e.g., through the European Commission’s Green Deal in 2019). The introduction of financial control mechanisms for more sustainable production, such as a CO₂ tax, as well as the evident scarcity of environmentally relevant resources, additionally indicate an increase in the cost of production. It will be an essential challenge for manufacturing companies to at least partially compensate for this increase in costs through more sustainable operations and counter sustainability-related risks to which they are exposed at an early stage.

2 Theoretical Foundations and Aim of this Publication

Research on sustainability assessment in production is, in principle, already quite advanced but still has specific weak points. These weaknesses were presented by Schneider et al. [5] and are summarised and discussed in Sect. 3. In contrast to the sole assessment of sustainability, sustainability modelling creates an abstract of reality using models, as this reality is usually too complex to be fully represented. However, completeness is not intended; rather, only the essential influencing factors significant for the real process and its context are to be identified and represented [6]. Following [7], a sustainability model of a production (system) should fulfil the following three characteristics: (1) representation of the original (i.e., production system), (2) shortening of the original’s attributes to those that seem relevant for the further purpose of use, and (3) pragmatism, since models have a replacement function tailored to specific addressees, time intervals and goals.

The concept of sustainability risk, on the other hand, has so far been discussed mainly at the country/sector level or regarding supply chain or product risks, but not yet with dedicated reference to production and its systems (cf. Section 3.3). Sustainability risks encompass environmental and social responsibility risks in addition to risks concerning the traditional bottom line [7]. The concept of sustainability risks becomes apparent when expressing the TBL mentioned above slightly differently: Normally, the TBL is defined as follows:

$$\text{Maximise: } F + E + S = \text{TBL} \quad (1)$$

In this formula, F describes the financial or economical performance, E the environmental performance, and S the social (responsibility) performance. Consequently, to maximise the sustainability of a manufacturing system, all three dimensions need to be considered. Following the general understanding of (financial) risk management, risk costs need to be subtracted from profit. Consequently, the TBL can be expressed monetarily as follows [7]:

$$\text{TBL} = F - \text{risk costs of E} - \text{risk costs of S} \quad (2)$$

It becomes apparent that the TBL, if measured in financial terms, is directly dependent on environmental and social risks or in other words: if the environmental and social responsibility risk costs are reduced while everything else is held constant, the TBL will

increase [7]. As displayed in Fig. 1, two different types of sustainability risks shall be distinguished in the following depending on their origin: physical risks and transitory risks. Physical risks are bidirectional and can either result from the environment and affect the production (e.g., extreme weather effects) or be caused by the production system and impact the environment (e.g., hazardous emissions and waste). Transitory risks, in contrast, are unidirectional and usually result from the changes in society to become more sustainable and tend to be regulatory and legal in nature (e.g., CO₂ tax). In Fig. 1, the difference between pure sustainability assessment and sustainability risk assessment also becomes apparent: While the former only considers the sustainability performance, the latter looks at the impacts of sustainability-related risks on manufacturing systems due to their sustainability performance.

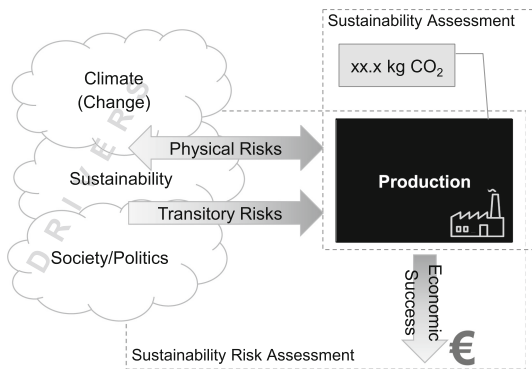


Fig. 1. Distinction between sustainability assessment and sustainability risk assessment

For an efficient sustainability risk assessment of production systems, however, a comprehensive information base is needed to describe the risk-relevant sustainability-related properties of the production system. This requires the sustainability modelling introduced above. Therefore, this paper aims to propose a research approach for modelling multidimensional sustainability to enable the identification and assessment of sustainability risks in production. This shall empower manufacturing companies, on the one hand, to report their sustainability performance to external stakeholders such as banks and customers, and on the other hand, to efficiently manage sustainability and related risks in manufacturing operations.

3 Literature Review and State of the Art

This chapter presents an overview of relevant preliminary work divided into the three sections sustainability assessment and modelling, data availability, and sustainability risks, according to the objectives of the research concept described above. Lastly, a need for action is derived.

3.1 Sustainability Assessment and Modelling of Manufacturing Systems

The state of the art in assessing manufacturing systems' sustainability performance was previously investigated extensively following different approaches [5, 7–11]. It became clear that various use cases for sustainability assessment systems exist, ranging from use as a tool in decision-making processes to operational support for process changes and help in conceptual design phases [5, 9]. Different assessment methodologies were also identified, which can be used to systematise the systems [5, 7, 8, 10]. Similarly, existing sustainability assessment systems have already been systematised according to the company levels considered and the sustainability dimensions covered [5, 11]. However, challenges remain in dealing with sustainability assessment systems. Firstly, there is a persistent lack of a generic sector-appropriate sustainability concept [12]. Secondly, an ongoing disagreement on fundamental aspects of the taxonomy of sustainability indicators becomes apparent [5]. This concerns, in particular, the dimensions and operational levels to be covered during the assessment. For example, few approaches exist for the segment/system, cell, and station level of a company that consider all three dimensions of sustainability according to the TBL. Often, only ecological and economic, or even only ecological, aspects are covered on these levels, while social factors are not or only marginally accounted for [5].

The state of the art of sustainability modelling can be described with less clarity. In particular, this is due to the inconsistent use of the term “model” or “modelling” in connection with the sustainability of production systems. Many publications regarding sustainability assessment also mention the term modelling (e.g., [13–17]). However, the use of the term ranges from being used synonymously with “assessment” to actually representing “modelling” in the sense of the requirements for a (sustainability) model defined above. At the same time, the majority of the actual models presented in these papers are not exhaustively backed by tools and technologies, nor do they support the complete manufacturing life cycle [18].

3.2 Data Availability in Manufacturing Systems for Effective Sustainability Assessment and Modelling

In general, sustainability assessment is very data-intensive [19]. The data basis required for sustainability assessment depends primarily on the assessment object. However, also the choice of the assessment method determines which data are needed for the assessment and in which format they must be available. One of the most widely used types of assessment methods is the so-called material flow-based assessment. The most typical representative of this type is the Life Cycle Assessment (LCA). Despite its high degree of standardisation according to the ISO 14040/14044 standard framework, LCA suffers from a lack of readily available data [20]. For manufacturing use cases, so-called inventory data, i.e., standardised and publicly available data regarding resource consumption and emissions, is typically limited to the production processes of primary materials [21]. This leaves a lack of manufacturing process-related inventory data, which would be essential for accurately assessing and modelling a manufacturing system's sustainability. The following publications, in particular, are among the approaches to solving or improving this problem, not only for LCA but sustainability assessment in general.

Bettoni et al. [22] defined a reference data model for sustainability assessment. Landolfi et al. [23] proposed a Manufacturing as a Service platform architecture to support data sovereignty for sustainability assessments of manufacturing systems. Aizstrauta and Ginters [24] used market data of technologies in their approach to building a sustainability assessment model. Li et al. [19] presented a data-driven approach for improving sustainability assessment in advanced manufacturing. In summary, it becomes apparent through these publications that there is a scientific need for converting and simplifying knowledge-based and data-driven models into analytics models for uniform employment in sustainability assessment [19].

3.3 Identifying and Assessing Sustainability Risks for Manufacturing Systems

The concept of sustainability risk was introduced with a focus on countries or industry sectors [7]. Publications regarding manufacturing companies have only recently appeared. Thereby, the main focus of many of these publications is on sustainability risks affecting procurement and supply chains. For instance, Torres-Ruiz & Ravindran [25] presented a framework for assessing potential sustainability risks of supply chains for different supplier segments. Similarly, Xu et al. [26] developed an assessment framework to evaluate supply chain sustainability by measuring operational risks, social risks, and environmental risks. Another group of publications considers sustainability risks of specific products. For example, Vinodh & Jayakrishna [27] proposed an evaluation model for sequential risk/benefit assessments throughout the product life cycle. Correspondingly, Anand et al. [28] developed a sustainability risk assessment index for the conceptual design phase of a mechanical system. In contrast to those two groups, only a few publications can be found focusing on the risk assessment of manufacturing systems. García-Gómez et al. [29] discussed criteria, methodologies, and requirements for identifying, analysing, and evaluating sustainability risks related to industrial assets. Kazancoglu et al. [30] focused their sustainability risk assessment approach specifically on the process of e-waste recycling for the circular economy. In summary, it can be said that although the topic of sustainability risk is receiving increasing attention in the context of the manufacturing industry, existing approaches are mainly limited to areas adjacent to production. However, an approach that explicitly addresses the sustainability risks of production and its systems is still missing.

3.4 Need for Action

Considering the limitations of the state of research presented above, it is evident that a comprehensive research approach is needed to achieve the goals set out in Sect. 2. On the one hand, this approach must enable the abstract modelling of the sustainability of production systems that is necessary for risk identification and assessment. And on the other hand, it must consider the required data basis and propose a method to determine and capture relevant information efficiently. Thereby, sustainability decision logic and model structures must be modularised to enable and streamline an ongoing sustainability risk assessment in production systems.

4 Concept for Sustainability Modelling and Sustainability Risk Assessment in Manufacturing Systems

The proposed concept comprises the three consecutive steps Modelling, Extracting, and Employing, and is outlined in Fig. 2. For the first step of modelling a manufacturing system's sustainability, a basis must initially be established for abstractly discussing sustainability. To do so, relevant sustainability-related key performance indicators (KPI) are identified and systematised in a use-case-specific taxonomy from the publications presented in [5] and above. The taxonomy is afterwards expanded by the collection and definition of calculation rules for the KPIs. This results in a calculation system to identify and describe the interdependencies between the taxonomy's KPIs.

The second step of determining and extracting relevant data is carried out based on the previously defined calculation system of KPIs. Initially, the required data basis and possibilities for data collection are assessed. Afterwards, the efficient collection of KPI-relevant data is intended. According to the current state of development, the approach is as follows: At the outset, process models and resource libraries are created semi-automatically based on data available in the production system. These are, among others, digital product and plant models containing sustainability-relevant information. Subsequently, a semi-automated matching of the processes and resources with existing Life Cycle Inventory (LCI) databases is conducted. Lastly, the generated process/resource models are linked with the existing LCI data to form an LCA model, thus enabling the automated calculation of KPIs in accordance with ISO 14040/14044.

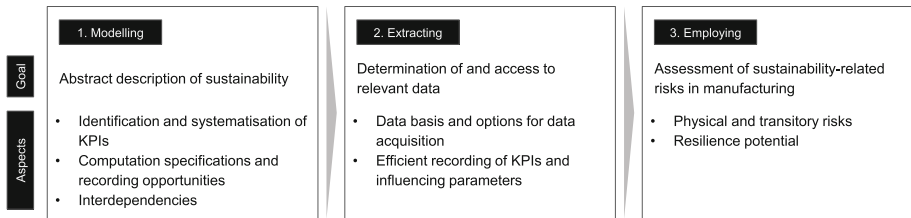


Fig. 2. Concept for sustainability modelling and sustainability risk assessment

The third step of employment uses the achieved KPI model to identify and assess sustainability risks in manufacturing. For this purpose, dimension-specific risk functions are defined and then used to quantify the degree of “damage” to be expected given certain decision functions. Thereby, the severity of damage directly depends on the calculated KPIs' values and, therefore, on the production system itself. The probability of occurrence, however, is mainly dependent on non-manufacturing-related circumstances (e.g., likelihood of stricter climate legislation). Therefore, from a production science perspective, the main focus is on quantifying the potential extent of damage based on the preceding sustainability modelling. The results shall be used, as described above, to report sustainability performance to external stakeholders and to manage sustainability and related risks in manufacturing operations efficiently. The latter serves to increase the sustainability-related resilience of manufacturing companies by identifying improvement possibilities.

5 Conclusion and Outlook

In summary, research on sustainability assessment in production is, in principle, already quite advanced but still has certain weak points. The concept of sustainability risk has so far been discussed mainly at the country/sector level or regarding supply chain or product risks, but not yet with dedicated reference to production and its systems. Therefore, the novelty value of the overall concept lies in the intended use of sustainability assessment to identify and evaluate sustainability risks in production. The proposed concept is currently developed also in cooperation with Commerzbank AG, a major German bank, where it shall be applied in the credit risk management function for corporate customers. The customers are German medium-sized companies in the machinery and plant engineering sector. Emerging sustainability requirements and climate effects impose risks on these manufacturing companies, thus also on the financing bank. These risks, however, can also represent opportunities as high-tech solutions sold by the companies often alleviate the harmful effects of production. They can thus mitigate or reduce the sustainability risks of their respective customers. While risk management in this field used to be focused on well-defined financial risks, it must now increasingly deal with sustainability risks and the sustainability-related resilience of its customers.

Acknowledgement. The authors would like to thank the German Federal Ministry of Education and Research (BMBF) and Jülich Project Management for funding the SynErgie Project (03SFK3E1 2) and Commerzbank AG for the excellent collaboration.

References

1. IPCC Climate Change 2014: Synthesis report, Genf (2014)
2. Stern, N.: The economics of climate change. Cambridge University Press, Cambridge (2007)
3. Brundtland commission our common future (1987)
4. Elkington, J., John, E.: Cannibals with forks: the triple bottom line of 21st century business. Capstone, Oxford, United Kingdom (1999)
5. Schneider, D., Paul, M., Vernim, S., Zaeh, M.F.: Sustainability assessment of manufacturing systems – a review-based systematisation. In: Andersen, A.-L., et al. (eds.) Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems. Lecture Notes in Mechanical Engineering, pp. 1023–1030. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-90700-6_117
6. Thalheim, B.: Towards a Theory of Conceptual Modelling. Verlag der TU, Graz (2010)
7. Stachowiak, H.: Allgemeine Modelltheorie. Springer, Wien (1973)
8. Anderson, D.R., Anderson, K.E.: Sustainability risk management. Risk Manag. Insur. Rev. **12**, 25–38 (2009)
9. Finnveden, G., Moberg, Å.: Environmental systems analysis tools – an overview. J. Clean. Prod. **13**, 1165–1173 (2005)
10. Ness, B., Urbel-Piirsalu, E., Anderberg, S., et al.: Categorising tools for sustainability assessment. Ecol. Econ. **60**, 498–508 (2007)
11. Moldan, B., Janoušková, S., Hák, T.: How to understand and measure environmental sustainability: indicators and targets. Ecol. Indic. **17**, 4–13 (2012)
12. Singh, R.K., Murty, H.R., Gupta, S.K., et al.: An overview of sustainability assessment methodologies. Ecol. Indic. **15**, 281–299 (2012)

13. Ahmad, S., Wong, K.Y., Rajoo, S.: Sustainability indicators for manufacturing sectors. *JMTM* **30**, 312–334 (2019)
14. Čuček, L., Klemeš, J.J., Kravanja, Z.: A review of footprint analysis tools for monitoring impacts on sustainability. *J. Clean. Prod.* **34**, 9–20 (2012)
15. Delai, I., Takahashi, S.: Sustainability measurement system: a reference model proposal. *Soc. Responsib. J.* **7**, 438–471 (2011)
16. Germani, M., Mandolini, M., Marconi, M., et al.: A method for the estimation of the economic and ecological sustainability of production lines. *Procedia CIRP* **15**, 147–152 (2014)
17. Krajnc, D., Glavič, P.: A model for integrated assessment of sustainable development. *Resour. Conserv. Recycl.* **43**, 189–208 (2005). <https://doi.org/10.1016/j.resconrec.2004.06.002>
18. Nicoletti Junior, A., de Oliveira, M.C., Helleno, A.L.: Sustainability evaluation model for manufacturing systems based on the correlation between triple bottom line dimensions and balanced scorecard perspectives. *J. Clean. Prod.* **190**, 84–93 (2018)
19. Zhang, H., Haapala, K.R.: Integrating sustainable manufacturing assessment into decision making for a production work cell. *J. Clean. Prod.* **105**, 52–63 (2015)
20. Ahmed, M.D., Sundaram, D.: Sustainability modelling and reporting: from roadmap to implementation. *Decis. Support Syst.* **53**, 611–624 (2012)
21. Li, Y., Zhang, H., Roy, U., et al.: A data-driven approach for improving sustainability assessment in advanced manufacturing. In: 2017 IEEE International Conference on Big Data (Big Data), pp. 1736–1745. IEEE (2017)
22. Finnveden, G., Hauschild, M.Z., Ekvall, T., et al.: Recent developments in Life Cycle Assessment. *J Environ Manage* **91**, 1–21 (2009)
23. Mani, M., Johansson, B., Lyons, K.W., et al.: Simulation and analysis for sustainable product development. *Int J Life Cycle Assess* **18**, 1129–1136 (2013)
24. Bettoni, A., Alge, M., Rovere, D., et al.: Towards sustainability assessment: reference data model for integrated product, process, supply chain design. In: 2012 18th International ICE Conference on Engineering, Technology and Innovation, pp. 1–10. IEEE (2012)
25. Landolfi, G., Barni, A., Izzo, G., et al.: A MaaS platform architecture supporting data sovereignty in sustainability assessment of manufacturing systems. *Procedia Manufacturing* **38**, 548–555 (2019)
26. Aizstrauta, D., Ginters, E.: Using market data of technologies to build a dynamic integrated acceptance and sustainability assessment model. *Procedia Comput. Sci.* **104**, 501–508 (2017)
27. Torres-Ruiz, A., Ravindran, A.R.: Multiple criteria framework for the sustainability risk assessment of a supplier portfolio. *J. Clean. Prod.* **172**, 4478–4493 (2018)
28. Xu, M., Cui, Y., Hu, M., et al.: Supply chain sustainability risk and assessment. *J. Clean. Prod.* **225**, 857–867 (2019)
29. Vinodh, S., Jayakrishna, K.: Assessment of product sustainability and the associated risk/benefits for an automotive organisation. *Int J Adv Manuf Technol* **66**, 733–740 (2013)
30. Anand, A., Khan, R.A., Wani, M.F.: Development of a sustainability risk assessment index of a mechanical system at conceptual design stage. *J. Clean. Prod.* **139**, 258–266 (2016)
31. García-Gómez, F.J., Rosales-Prieto, V.F., Sánchez-Lite, A., et al.: An approach to sustainability risk assessment in industrial assets. *Sustainability* **13**, 6538 (2021)
32. Kazancoglu, Y., Ozkan-Ozen, Y.D., Mangla, S.K., Ram, M.: Risk assessment for sustainability in e-waste recycling in circular economy. *Clean Technol. Environ. Policy* **24**(4), 1145–1157 (2020). <https://doi.org/10.1007/s10098-020-01901-3>