Global Journal of Flexible Systems Management (June 2023) 24(2):271–289
https://doi.org/10.1007/s40171-023-00339-y

ORIGINAL RESEARCH

Manufacturing Flexibility through Industry 4.0 Technological Concepts—Impact and Assessment

Kristina Höse[1] · **Afonso Amaral**[2] · **Uwe Götze**[1] · **Paulo Peças**[3]

Received: 25 August 2022 / Accepted: 19 March 2023 / Published online: 13 April 2023

Abstract *There is an ever-growing need for companies and manufacturing systems to be flexible in order for them to adapt to the rapid changes and increasing uncertainty in society, markets, and supply chains. Several studies suggest that Industry 4.0 solutions foster shorter innovation/development cycles, resource efficiency, individualization on demand, faster decision making, and, finally, higher flexibility in production. However, little is still known about the relationship between Industry 4.0 and manufacturing flexibility. One of the existing gaps in the literature is the lack of a methodology to assess the potential impact of Industry 4.0 solutions on manufacturing flexibility and companies' profitability. This paper contributes to closing such a gap from a theoretical perspective. First, it conceptualized the role of flexibility in manufacturing systems. Then, the relationship between Industry 4.0 solutions and manufacturing flexibility was analyzed on a conceptual level, in which the I–T–O model was used to distinguish between the needed and available flexibility. Lastly, based on a decision-theory-based procedure model, a methodological approach for evaluating Industry 4.0 solutions is suggested. This methodological approach is intended to support transparent assessments tailored to different technological concepts as well as the affected types of flexibility (available and needed). It is able to integrate existing methods from decision and investment appraisal theory as well as specific flexibility-related approaches. The results of the paper will be useful for both academicians and practitioners. Besides enabling quantitative evaluations, the methodological approach can be used by companies as a structured path to explore the possible ways they can increase their manufacturing flexibility.*

Keywords Evaluation · Industry 4.0 (I4.0) · I4.0 technological concepts · Manufacturing flexibility · Methodological approach

Introduction

Over the past several decades, the rise of globalization and production outsourcing, and their inherent environmental complexity and uncertainty, have become major obstacles that companies and their decision makers must address. Additionally, rising customer requirements have resulted in higher demand for customized products and, therefore, a higher need for product variety and shorter product life cycles (Brettel et al., 2014). Consequently, companies increasingly need to be able to react to this dynamic and uncertain context—in other words, there is a growing need for companies to be flexible (Mascarenhas, 1981; Sassanelli & Terzi, 2022). This especially holds true for the manufacturing systems of industrial companies (Cingöz & Akdoğan, 2013).

At the same time, such companies have been challenged and enabled by the megatrend of digitalization. One important sub-trend of digitalization is the shift toward Industry 4.0 (I4.0), a concept firstly mentioned in the High-Tech Strategy 2020 of the German government (Lasi et al.,

---

✉ Kristina Höse
kristina.hoese@wiwi.tu-chemnitz.de

[1] Chair of Management Accounting and Control, Chemnitz University of Technology, Reichenhainer Straße 39/41, 09126 Chemnitz, Germany

[2] Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais 1, 1049-001 Lisbon, Portugal

[3] IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais 1, 1049-001 Lisbon, Portugal

2014). I4.0 was suggested against the background of the following trends and conditions: short innovation/development cycles, the need for resource efficiency, individualization on demand, the need for decentralization to enable faster decision making, and the necessity of higher flexibility in production (Lasi et al., 2014). I4.0 is expected to provide greater flexibility to the worldwide industrial sector while increasing the quality standards of typical industrial processes (Castro-Martin et al., 2021; Fernandes et al., 2021). Hence, I4.0 is a concept that promises to contribute to fulfilling the increasing need for flexibility.

To date, the literature has already contemplated tools to help companies endure in I4.0 endeavors (Erol et al., 2016) and provided examples of technological implementation to show that the entry barriers of companies to I4.0 are perhaps not as high as they seem to be (Amaral & Peças, 2021a; Kumar et al., 2022; Saha et al., 2022). However, the literature has not yet provided an understanding of the real impact that I4.0 will have on existing manufacturing systems. While it is generally accepted that the implementation of I4.0 technologies will boost manufacturing flexibility, most existing papers focus on specific case studies or segments of the manufacturing process. Still, any positive effects of the implementation of I4.0 technological concepts on flexibility will not automatically result in the higher profitability of companies, as this implementation will be accompanied by investments. As such should be included into the consideration of I4.0 technological concepts and their influence on flexibility, it should be considered in a model with the goal to evaluate the impact of I4.0 to flexibility. This paper contributes, therefore, to the following existing gaps in the literature. First, expanding our knowledge about the relationship between I4.0 and manufacturing flexibility is needed. Second, while there are already several models that help companies deal with the implementation of I4.0 technologies (Amaral & Peças, 2021b; Pessl et al., 2020; Santos & Martinho, 2019), there is a need for a method that systematically assesses the profitability of I4.0 technological concepts under the explicit consideration of the affected types of flexibility.

This paper aimed to contribute to fulfilling both of these needs from a theoretical perspective. Firstly, the role of flexibility in manufacturing systems was conceptualized by describing the term itself, the possible contributions of flexibility to the target system of a given company, and the different types of flexibility in manufacturing systems. Additionally, the existing literature on I4.0 and flexibility is discussed (Sects. "Flexibility and its role in manufacturing systems" and "Industry 4.0 impact on flexibility"). The relationship between I4.0 technological concepts and manufacturing flexibility was also analyzed on a conceptual level in order to answer the first question raised above (Sect. "Industry 4.0 impact on flexibility"). In their essence, I4.0 solutions can either enhance the flexibility available in a manufacturing system or reduce the flexibility that is needed in such a system (e.g., by providing more or better information). Therefore, the existing I4.0 technological concepts were examined regarding whether their implementation will affect i) the available flexibility and ii) needed flexibility in the production sector. To provide a methodical base for answering the second question—how to evaluate the economic consequences of flexibility-changing activities in the form of investments in I4.0 technological concepts—an overview of the already existing evaluation methods is provided (Sect. "Overview of existing approaches"). This includes generally applicable methods from decision and investment appraisal theory, as well as specific flexibility-related approaches (e.g., of Azzone & Bertelé, 1989; Zäh et al., 2006). Afterwards, a methodological approach for the evaluation of I4.0 solutions is suggested (Sect. "Methodological Approach for Assessing Flexibility-Influencing Industry 4.0 Activities"). This approach is intended to enable transparent assessments tailored to the different I4.0 technological concepts, as well as the affected types of flexibility (available and needed). The methods outlined in Sect. "Overview of existing approaches" were integrated into the methodological approach.

The potential of the proposed theory-based procedure model to be used as a structure path for companies to explore the possible ways they can increase their manufacturing flexibility is discussed in Sect. "Discussion and Conclusions."

Flexibility and its Role in Manufacturing Systems

Taking chances and avoiding the threats of changing environmental conditions force companies to be more flexible (Jacob, 1989, p. 16). The word "flexibility" is used quite differently across several scientific and industrial fields and in different contexts. A general definition is given by Jacob. He defines flexibility as the property of an item (e.g., a machine or a manufacturing system), an institution (e.g., a company or a part of a company) or an activity to adapt itself to changing conditions and tasks that are changing due to new conditions (Jacob, 1989). Flexibility is often discussed in the context of companies, especially regarding their manufacturing systems. Correa identifies two main reasons flexibility is needed in such manufacturing systems: company-external uncertainty, which induces a need to respond to the unexpected, and the required variability of processes and products (Corrêa, 1992; De Toni & Tonchia, 1998, p. 1593; Solke et al., 2022; Sushil, 2009).

To understand the role manufacturing flexibility plays in a company, its possible contributions to the fulfillment of a company's targets and its corresponding positions in a company's target system should be analyzed. The target system of a company normally includes formal targets (initial targets) and supporting targets (Heinen, 1990). Achieving long-term existence and profit maximization are initial or formal targets of companies (Fuhrmann, 1998; Mikus, 2009). The achievement of these initial targets is enabled by fulfilling supporting targets such as minimizing capital investment and ensuring high-product quality (Mikus, 2009, p. 42). Flexibility can be included in a target system as (i) a means to reach other targets or (ii) as its own—supporting—target figure (Thielen, 1993). In the case of (i), manufacturing flexibility, as well as the different "sub-flexibilities" of the manufacturing system, assists with reaching other supporting targets and, directly or indirectly, the initial targets too (for a detailed analysis of the impact of flexibility on the input, process and output objectives in a manufacturing system see Corrêa, 1992). Additionally, or alternatively, in the case of (ii), different kinds of manufacturing flexibility can be understood as a company's own supporting targets (e.g., Mikus (2009) mentions production and product flexibility as supporting targets).

However, which types of manufacturing flexibility can be distinguished? De Toni and Tonchia classified the types of manufacturing flexibility based on a literature study. They identified four classification logics: horizontal (by phases), vertical/hierarchical, temporal and by the object of variation (De Toni & Tonchia, 1998). The most common of these in the literature is the classification of flexibility by the object of variation. Regarding this differentiation, one of the most cited divisions of the flexibility of manufacturing systems is that of Browne et al., who differ between machine, product, process, operation, routeing, volume, expansion, and production flexibility (Browne et al., 1984). Sethi and Sethi used this classification and added material handling, program, and market flexibility (Sethi & Sethi, 1990). Other divisions of flexibility exist, too, according to Azzone and Bertele, e.g., production, product, operational, mix, volume, and expansion flexibility (Azzone & Bertelé, 1989). As the classifications of the types of flexibility are very heterogeneous, it is not surprising that their definitions differ, too (for more definitions of the kinds of flexibility, as well as structuring possibilities, see Sethi & Sethi, 1990). In particular, from the point of view of managing a manufacturing system, the temporal classification logic seems to be very relevant. This distinguishes between instantaneous flexibility (e.g., in the form of an immediate selection of the most suitable work center during the production process), long-term flexibility (e.g., having the possibility to adjust the whole system to manufacture completely new products), and several kinds of flexibility in between (very short-term, short-term, short- to medium-term, medium-term, and medium- to long-term flexibility) (for a detailed description, see De Toni & Tonchia, 1998; Merchant, 1983).

In this paper, the Input–Throughput–Output-model (I–T–O model) was used to classify the different types of manufacturing flexibility. This model has been proven to provide a useful basis for modeling, structuring, analyzing, and designing different kinds of processes, especially the production processes considered in this paper (for more about the I–T–O model, see Götze et al., 2010a; Götze et al. (2011)). A classification involving input, process, and output flexibility has also been suggested by Sawhney. He distinguishes between the input, process, and output stages in a manufacturing company and identifies different kinds of in-house flexibility within these different stages (e.g., volume flexibility as a part of output flexibility). Additionally, he considers external flexibility that derive from the supply chain, such as customers and suppliers (Sawhney, 2006). In line with the I–T–O model and the thoughts of Sawhney, product-related (or output)[1] flexibility, process-related (or throughput) flexibility, and resource-related (or input) flexibility were distinguished in this paper (see Fig. 1).

The fundamental considerations made above about the role of flexibility in manufacturing systems provide a base for the following analysis of the impact of I4.0 solutions on flexibility, as well as the economic assessment of these solutions.

Industry 4.0 Impact on Flexibility

In the previous section, the I–T–O model was presented to distinguish between the types of flexibility in a production line. In this section, we conducted a literature-based analysis of the way in which I4.0 technological concepts can impact manufacturing flexibility. By providing a conceptualization of the impacts of I4.0 technological concepts on available and needed flexibility, we aimed to improve the understanding of the relationship between I4.0 and manufacturing flexibility.

I4.0 is a digital-transformation-related concept that involves an inherent deployment of technologies not only in a company's in-house processes but also in its whole supply chain (Lichblau et al., 2015). Some of these technologies, such as additive manufacturing or autonomous robots, are typically found in manufacturing shop-floors, while others, such as big data or e-value chains, are involved in the relationships between companies and their external environments, such as the relations of

---

[1] Although products are not the only kind of output (unintended outputs such as waste do exist as well), for the sake of simplicity, product flexibility and output flexibility are seen as being equal here.

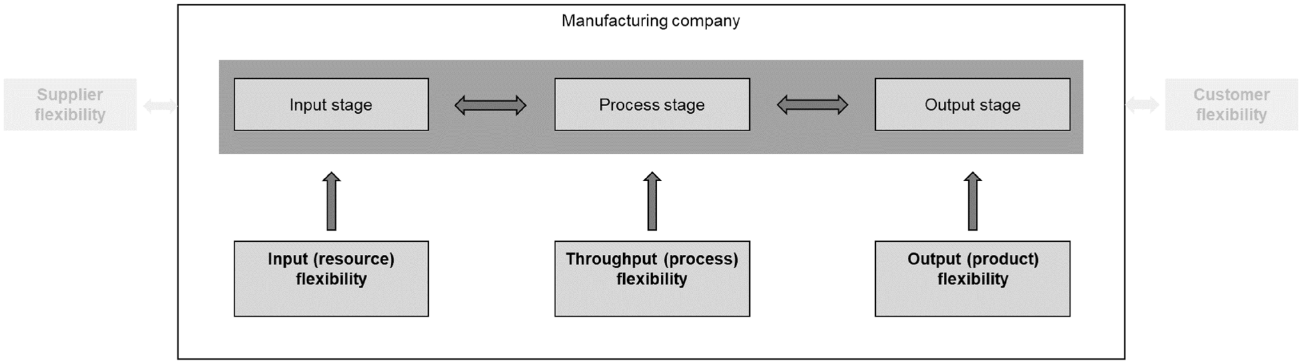

Fig. 1 Manufacturing flexibility based on I–T–O model (based on Götze et al., 2010a; Sawhney, 2006)

manufacturers with their customers or upstream suppliers (Bibby & Dehe, 2018). The true impact that I4.0 will have on different manufacturing technologies and practices is still to be seen, but there are already studies that have highlighted preliminary, positive results (Ali, 2012; Enrique et al., 2022).

Over the past decade, studies have proposed different methodologies for analyzing the impact of I4.0 factors influencing the levels of existing flexibility (Jain & Raj, 2013). Meanwhile, other studies have attempted to measure operational flexibility by using mathematical models (Sajjad et al., 2022) to model flexible production systems through Petri nets (Long et al., 2017), as well as carrying out simulation experiments to analyze the impact of routing flexibility (Ali and Murshid 2016). These, and other hands-on studies (Contador et al., 2020; Wadhwa et al., 2010), while relevant to this field of research, lack a more overarching theoretical dimension, which can be found in works such as Javaid et al. (2022), in which the authors explored the impact of I4.0 on flexible manufacturing systems' capability (Javaid et al., 2022).

Similar to our work, Salunkhe and Berglund (2022) studied the influence that I4.0 will have on operational flexibility (Salunkhe & Berglund, 2022). This work, however, failed to grasp the full scope of such an impact, as it only focused on final product assembly. Our work explores how I4.0 will impact firms' manufacturing flexibility, an area that has been previously highlighted to be lacking in the existing literature (Mishra et al., 2014). As explained in the next section, the impact of I4.0 technological concepts on flexibility is twofold: Firstly, there are I4.0 technological concepts that directly impact in-house manufacturing processes when they are implemented within them, therefore affecting in this way the available flexibility levels of these processes; secondly, some of the existing I4.0 technological concepts impact the necessary level of flexibility. The distinction between these two impacts is explained in the following subsections (3.1 & 3.2). Further, in these subsections, the fundamental considerations discussed above regarding the role of flexibility in manufacturing systems are used for an analysis of the impacts of I4.0 solutions on flexibility.

Impact on the Available Level of Flexibility

The impact of I4.0 on flexibility is twofold, and it can be analyzed through two different perspectives. The first is the "available level of flexibility," which refers to the flexibility level that is available within a company's manufacturing system with regard to its products, processes, and resources. One way to analyze this influence is through the use of the I–T–O model presented in Sect. "Flexibility and its role in manufacturing systems" (see Sawhney (2006)). In this study, the available flexibility related to the elements of this model was matched with the technological concepts of I4.0 (Bibby & Dehe, 2018) to determine where these technologies impact manufacturing flexibility. Table 1 presents the results of this matching, although we do not claim this to be complete.

There are four technological concepts that have a positive influence on all the elements of the I–T–O model and on the level of available flexibility: the AM, autonomous robots, IoT/CPS, and cloud concepts. The cloud technological concept, for example, enables a company to use another firm's machinery to increase the available number of working machines for a certain process, in order to fulfill a customer's requirement (Helo et al., 2014). This enables, in this case, the realization of different levels of production volume, directly affecting the available level of manufacturing flexibility in a specific process.

In contrast, the technologies related to the e-value chain have no impact on the available level of flexibility, although in the model proposed by Sawhney (Sawhney, 2006), there is a relation between the flexibility of suppliers and customers and the flexibility available in in-house processes. Sawhney demonstrates how in-house flexibility can be affected by external existing types of flexibility (Sawhney, 2006).

Table 1 Impact of industry 4.0 technological concepts on the available level of flexibility

Available level of flexibility		Industry 4.0 technological concepts							
		AM	Cloud	MES	IoT and CPS	Data Analytics	Sensors	e-Value Chain	Autonomous Robots
I–T–O model	Input	Allows adjustment of the number of machines	Allows desired number of (connected) machines (out of a company's scope)		Allows desired number of (connected) working machines				Allows adjustment of the number of robots (autonomously)
	Throughput	Process time and quality adjustable	Connected machines might have different features enabling different parameters in the process	Aids in the adjustment of orders in planning	Allows the rearrangement of existing machines, increasing occasional process capacity	Might suggest new or optimal ways of rearranging the existing machines	Allow machines to have different levels of precision (parameters)		Process time and quality adjustable (machine hours)
	Output	Same machine can produce different product variants	Allows varied production volume and product variation/ quality	Allows different product delivery rates	Allows varied production volume	Might allow varied production volume or variety	Precision enabled by sensors allows varied product quality		Allows different variants of products and varied production volume

AM: Additive manufacturing, *MES*: Manufacturing execution system, *IoT*: Internet of things, *CPS*: Cyber-physical systems

Indeed, some I4.0 technological concepts impact the level of uncertainty that companies face, either internally or externally (McAfee, Brynjolfsson 2012). For example, the e-value chain is a concept that is boosted by connectivity across the value chain, which provides transparency to create a dynamic environment that supports customer and supplier activities (Bibby & Dehe, 2018). Through the deployment of such technologies, companies can be more aware of, for example, market fluctuations, the types of products desired by consumers, and machine breakdowns from partners. This means that e-value chain technology action areas are exogenous to companies, and therefore, the existing available level of flexibility in (in-house) manufacturing processes is not affected by the deployment of e-value chain technologies. This is the reason why the column in Table 1 corresponding to the "e-value chain" technological concept is empty.

According to the above analysis, it can be affirmed that the impact of some I4.0 technological concepts on flexibility can be comprehended as a potential increase in the existing available level of the flexibility of companies. Further, using Table 1, one can understand the ways different I4.0 technological concepts impact the existing available level of the flexibility of companies.

Impact on the Necessary Level of Flexibility

Before presenting the second perspective, the influence of I4.0 on the necessary level of flexibility, it is vital to clarify the terms "data" and "information" to avoid any misunderstandings in the reasoning that follows. On the one hand, data can be understood as symbols that define the characteristics of objects and events. On the other hand, information consists of processed data, which are useful for businesses and organizations (Targowski, 2014). In other words, data consist of pure symbols without a context, while information can be perceived as contextualized data.

Flexibility can be seen as a fundamental instrument for "dealing with uncertainty "(Rocky Newman et al., 1993). Therefore, a decrease in the external uncertainty triggers a reduction in a company's necessary level of flexibility. This reduction results in an increased awareness that arises from the new insights gathered by the company and enables it to be prepared in a way that was not feasible before. The second perspective is, thus, the level of flexibility required for a company's internal processes to operate. Hence, I4.0 technological concepts can help a company to reduce its necessary level of flexibility and accurately tune its level of flexibility to that perceived by the company to be necessary.

In this regard, LaValle et al. (2011) explained tools such as data visualization, process simulation, text and voice analytics, and social media analysis, as well as further predictive and prescriptive techniques, that are able to convert data into either insights or information. Therefore, in this paper, two means a company can use to reduce its level of uncertainty are distinguished, one related to the extraction of insights and the other related to information retrieval. This differentiation is supported by the claim that an organization's analytics process can be divided into two different uses: the use of analytics and the use of information (LaValle et al., 2011). In this regard, the first method is the (1) "extraction of insights from data analytics," which essentially refers to the transformation of data into useful information. This incorporates any type of insight extracted using data analytics algorithms, regardless of where the data were collected from. The second method is (2) "the acquisition of provided information," which refers to the information that is provided to a company by external sources. This can take place through communication channels such as the telephone, e-mail, company website, and social media.

Both of the methods referred to in the previous paragraph feature different types of data/information inputs. The relationship between the methods of impacting manufacturing flexibility and their data/information inputs is shown in Figs. 2 and 3. Figure 2 illustrates both ways that data—derived from (a) a "data analytics input generator"—can be transferred until it is used by a data analytics program. Data can be conveyed either through (b) a "data analytics input conveyor," for example, data that are generated in a sensor and transferred through the IoT to a database, and/or through (1) programs (software) that aggregate data, on top of which data analytics algorithms can be run. The middle part of Fig. 3 represents the straightforward relation between (c) an "information

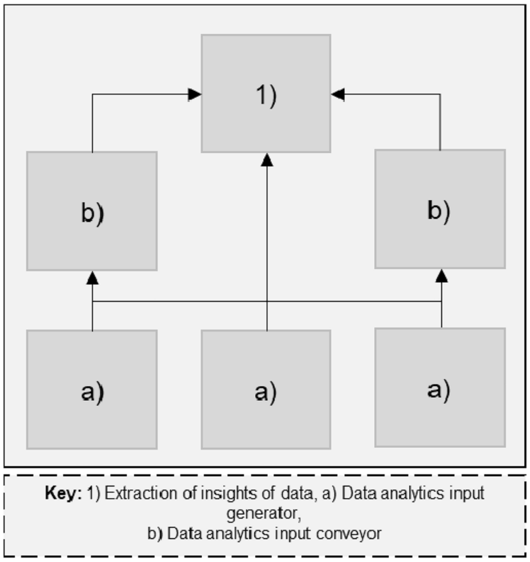

Fig. 2 Extraction from data analytics and its inputs

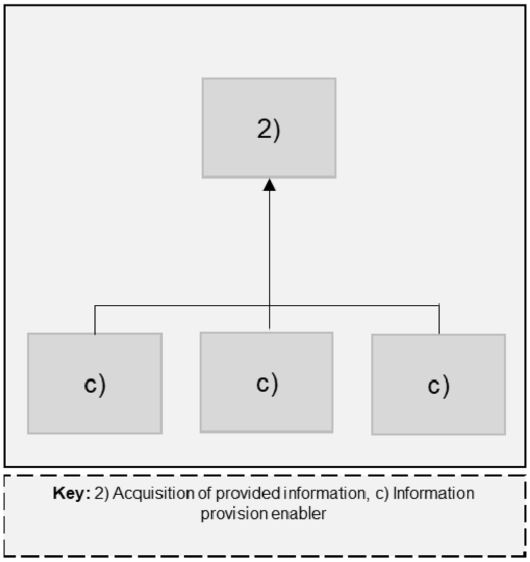

Fig. 3 Acquisition of provided information

provision enabler" and (2) the "acquisition of that (same) provided information," assuming that such information is available or is made available with the deployment of special programs.

Furthermore, both possible methods of impacting the necessary level of flexibility are only feasible if supported by at least one of the following described types of data/information inputs: (a) a data analytics input generator, (b) data analytics input conveyor, and (c) information provision enabler. The first two types of inputs are channels that permit (1) "the extraction of insights from data" (left part of Fig. 2). First, a), the first type of input can be conceived of as a sensor, since it generates data from the surrounding environment, and is thus categorized as a "data analytics input generator." Second, the other type of input, (b), can be interpreted as the connection (either by cable or wireless) between a sensor and the database (where the data are stored) and is thus classified as a "data analytics input conveyer." The third input is a channel that connects a company with its external partners and customers to allow information exchange, permitting the company to perform (2) "the acquisition of provided information." The difference between inputs (b) and (c) is that while (b) conveys data from, for example, sensors to its storage, (c) connects the company with other entities, allowing information to be transferred from one side to another. In this regard, (c) can be perceived of as a platform that gathers both suppliers and customers and enables information to flow from external sources to the company and is thus classified as an "information provision enabler."

This proposed architecture is essential if a holistic but precise understanding of I4.0's impact on flexibility is to be achieved. Each technological concept can be thought of as either a generator of a type or types of data/information input(s) {(a), (b), (c)}, or as a method for impacting the perceived necessary level of a company's flexibility directly {(1), (2)}. Below, each I4.0 technological concept is analyzed through the perspectives described in the previous paragraphs, with their impact, either direct {(1), (2)} or indirect {(a), (b), (c)}, on the necessary level of flexibility discussed.

Sensors—(a) Sensors generate raw data; thus, they are considered (a) "data analytics input generators." These data can be used for data analytics so that insights can be extracted from them. Sensors collect data from manufacturing processes (throughput) and can also collect data on the kinds of materials being used in these processes (input) and the type/quality/number of the finished products that exist (output).

MES—(a) These programs generate data and information by combining the raw data from the shop floor (Saenz de Ugarte et al., 2009) so that they can be used by workers and data analytic programs; they are thus categorized as a) "data analytics input generators" (throughput, input, output). It is worth keeping in mind that although this aggregation of data permits the MES program to generate data and information, the raw data that it absorbs can also be used by data analytics programs.

IoT and CPS—(b), (c) This technological concept is the only one that is considered both (a b) "data analytics input conveyer" and (c) "information provision enabler." On the one hand, it can be considered an "information provision enabler" because it enables connections between a company and its customers and/or suppliers (output, input), as well as connections among different machines (M2M) and between machines and users (H2M) (throughput). On the other hand, it can be considered a "data analytics input conveyer" since it conveys data from the sensors all the way to its storage, where analytics algorithms can be run (input, throughput, output).

Cloud—(a), (c) The cloud is the only technological concept that is both a (a) "data analytics input generator" and (c) "information provision enabler." On the one hand, it is an information provision enabler because it connects companies with customers (output); on the other hand, it is (a) "data analytics input generator" because it can store data from either processes, resources, or products (input, throughput, output).

Data Analytics—(1) The insights extracted from either internal or external data allow a company to better determine, for example, what a certain customer wants in a certain moment in time. Having this knowledge helps the company produce what the customer really wants, and thus less product types (output) are produced; subsequently, the number of manufacturing processes might be reduced (throughput). All of this can result in a more targeted procurement (input). Consequently, data analytics is considered to belong to the (1) extraction of insights from data analytics category.

E-value Chain—(2) The permanent connection with a client, granted by e-value chain technologies, allows the company to know what the client really wants. If a less diverse number of product types need to be produced (output), then less variance in the company's manufacturing processes is necessary (throughput), resulting in a reduction in the type of resources (input). Therefore, the e-value chain is considered to belong to the (2) acquisition of provided information category.

Additive Manufacturing and Autonomous Robots Both of these technological concepts are deployed on the shop floor. Neither of these technologies impact the necessary level of flexibility, because they are deployed in in-house processes and do not necessarily generate data. Only if they are coupled with specific sensors, can these technologies produce data—however, "sensors" are themselves considered an I4.0 technological concept. Therefore, these two technologies are proposed to not impact by themselves the necessary level of technology.

To conclude, implementing I4.0 technological concepts can help companies manage their level of manufacturing flexibility. These technologies can impact companies in two different ways, either by increasing the level of flexibility available in a company's processes or by assisting the company adjust the level of flexibility required to carry out these processes. Further, as these technologies can have different impacts on flexibility, the two provided perspectives in this section can assist in comprehending how such technologies impact flexibility. As can be understood from Table 1 and the analysis performed above, some technological concepts directly affect flexibility in both ways, and others impact it strictly through just one. In summary, the results of Sect. "Industry 4.0 impact on flexibility" provide a conceptualization of the relationships between I4.0 technological concepts and manufacturing flexibility.

Assessment of Flexibility and Flexibility-Related Measures

Overview of Existing Approaches

Section "Industry 4.0 impact on flexibility" emphasized the ways in which I4.0 technologies can influence manufacturing flexibility—in some cases, their implementation may result in a decreasing (or increasing) need for flexibility, and in other cases in an increasing (or decreasing) level of available flexibility. What consequences, however, does a change in the level of flexibility have on the profitability of companies, and how can this be evaluated? This section is intended to contribute to answering these questions. In Sect. "Overview of existing approaches," an overview of existing approaches is provided through a literature review. In Sect. "Methodological Approach for Assessing Flexibility-Influencing Industry 4.0 Activities", our own methodological approach is suggested.

In general, two perspectives for analyzing and evaluating flexibility can be distinguished—first, there is the assessment of the grade of flexibility, and second, there is the evaluation of the profitability of concrete activities that have an influence on the degree of flexibility. Concerning the grade of flexibility, it is expected that an appropriate flexibility level, rather than the maximum level of flexibility, will result in the best economic consequences in any case, as the maximum level of flexibility may cause complete instability (Thielen, 1993) and may be too expensive. However, an appropriate or even optimum level of flexibility is hard to identify. Additionally, the identification of the level of flexibility does not assist in making a clear statement of the profitability of flexibility-changing projects (Azzone & Bertelé, 1989; Zäh et al., 2006). Therefore, this paper focused on the second perspective: the assessment of I4.0 actions or projects that influence flexibility (see also Bellmann et al., 2009 for an evaluation of flexibility in general). Consequently, this section is intended to give an overview of existing assessment methods. Firstly, these comprise approaches that are generally used to analyze investment objects, including those with an influence on flexibility. Additionally, approaches that have been specifically suggested to be used for evaluating flexibility-related actions were considered.

Approaches to Assess Action Alternatives that Influence Flexibility

Checklist/Utility Value Analysis One method used to perform systematic evaluations is checklists. The structure and content of checklists, e.g., assessment criteria, can be individually defined based on the experience of the decision maker (Vahs, 2014). The criteria can include factors that describe flexibility or reflect the impact of flexibility-related actions. Nevertheless, this method lacks the facilitation of a significant assessment, as no weighting or concrete determination of the outcomes of criteria exist.

To achieve higher significance, utility value analysis can be used, as this supports multi-criteria decision making and considers the weightings and concrete outcomes of criteria. After the definition of target criteria, each criterion is weighted. (The criteria of a checklist can obviously be used, if the checklist is carried out before the utility value analysis.) Afterward, the partial utility values are determined based on the outcomes of the criteria. Finally, total utility values for each alternative can be calculated to assess their profitability. (For more details about utility value analysis, see Götze et al., 2015.) Utility value analysis is a well-structured evaluation method for cases of multi-criteria decision making and has easily interpretable results. However, it has challenges related to data collection, and utility values are based on subjective judgements (Götze et al., 2015). Regarding I4.0 actions, utility value analysis enables a comparison of different flexibility-influencing alternatives (e.g., the integration of different kinds of sensors within a production process). Therefore, flexibility-related target criteria, e.g., the complexity of the work process and susceptibility of errors, can be included in the assessment of alternatives.

Net Present Value Method under Uncertainty Both checklists and utility value analysis do not focus on monetary assessment. For monetary evaluation, several dynamic investment appraisal methods exist. The most accepted and established is the net present value (NPV) method (Götze et al., 2015; Hopkinson, 2017), a dynamic method that takes the time value of money into account. Therefore, all cash flows resulting from an investment (e.g., initial investment outlay, liquidation value, etc.) are discounted to a common point of time (e.g., $t = 0$) to determine whether the investment alternative is absolutely profitable (NPV $>$ 0) and/or relatively profitable (NPV of the investment being higher than NPV of another investment). In the method's practical applications, data collection is often a huge challenge, especially regarding the forecast of the in- and outflows. Additionally, assumptions such as a perfect capital market and knowledge of the relevant data are to be considered (Götze et al., 2015).

Regarding I4.0, the NPV method allows for comparing processes, projects and investments without and with the application of I4.0 technological concepts and/or different means of realizing I4.0. Concerning flexibility, the cash outflows of activities for increasing flexibility can be included in the series of cash flows without additional methodical challenges (beyond the normal challenge of forecasting the data). However, regarding the positive effects of flexibility, this is different. One positive effect of flexibility, for instance, is the better adaptability of the system to the (uncertain) future developments of relevant parameters, such as technologies, prices, sales, and production volumes. Therefore, the positive effects of flexibility can only be revealed if uncertainty is explicitly included in the model when assessing the flexibility-related alternatives. This can be achieved by formulating scenarios for uncertain parameters that induce a need for flexibility and forecasting the cash inflows and outflows dependent on these parameters for each alternative. These reflect the positive effects of flexibility-influencing alternatives. Afterward, NPVs for each scenario and alternative can be calculated. The total number of NPVs of an alternative—possibly summarized as an expected value of NPVs—expresses the profitability of the alternative.

The calculation of NPVs for different scenarios can be understood as a type of sensitivity analysis. In general, sensitivity analysis intends to study the relations among the effects of the several—uncertain—data, on the target values of an investment object, as well as the profitability of alternatives. Sensitivity analysis operates in the following ways: either input data are varied systematically (e.g., in the form of scenarios) and the resulting target values of an alternative are calculated, or the critical values of an input figure that result in a given target value such as NPV = 0 are determined. A related approach, the so-called risk analysis, aims to outline uncertain input figures in the form of probability distributions. This method considers interdependencies among input figures, as well as between input and target figures. As a result, the derivation of a probability distribution for different possible target values is enabled, e.g., by a Monte Carlo Simulation. This method's analysis provides decision making under uncertainty (Götze et al., 2015). Both methods can be applied for evaluating I4.0 projects in general and specifically regarding their impact on flexibility, such as outlined in the above paragraph.

Using the NPV calculations under uncertainty described above, flexibility-related alternatives that are planned to be realized in different points in time can be included as well. Nevertheless, this requires a fixed plan of actions for which an NPV is calculated. The decision tree method offers the additional option of including flexibility-related reactions as a result of additional information that is expected to be available in the future. Within this method, different scenarios and their resulting profitability are the objects under consideration as well. Additionally, included are follow-up decisions that have to be made depending on the state (scenario) reached in a future point in time—considering that information about the development that results in this specific state is available. This development will influence the expectations for future development, so it is state-specific as well, possibly resulting in different follow-up decisions for each state. These decisions and their effects on the future cash flows and the NPV are included in the calculations as well. The optimum alternative is again the one with the highest expected NPV—which here takes the effects of future decision making into account. Challenges regarding the application of this method arise from its complexity and the additional need for data on the inclusion of different scenarios, as well as scenario-specific future decisions (Götze et al., 2015).

The decision tree method can generally be used for the assessment of I4.0 projects. Since the option to be realized and the profitability of future alternatives is strongly coupled with flexibility and possibilities to react to new modeled information, the method is considered flexible—and it is predetermined to evaluate options for enhancing flexibility in this regard.

Flexibility-Specific Approaches

Besides the generally applicable methods described in the previous paragraphs, some other approaches do exist that are explicitly intended to evaluate flexibility-related actions. Azzone and Bertele (1989) proposed a method consisting of three steps: 1. analyzing a company's strategic position by indicators; 2. measuring different kinds of flexibility; and 3. calculating the NPVs (or internal rates of return) of investments, including the costs of increased flexibility and the additional cash flows achieved by means of a higher flexibility, to determine its economic potential in the manufacturing domain (Azzone und Bertele 1989).

Thielen (1993) evaluated flexibility by identifying the costs (e.g., real costs such as the capacity reserves of machines and opportunity costs) and benefits (e.g., in the form of saving costs or avoiding the costs of inflexibility) of flexibility. For the assessment, he proposed a cost–benefit analysis (Thielen, 1993).

A software-based method for the life-cycle-oriented assessment of flexibility in production was proposed by Zäh, et al. (2006). Firstly, relevant types of flexibility are identified. Then, uncertainties (e.g., demand trends) are modeled using a Monte Carlo simulation. This addresses uncertainty, as uncertainty is a basic reason for the necessity of flexibility (as explained in the earlier sections). Finally, the costs of different scenarios as a result of the several kinds of flexibility and uncertainty are calculated in the form of NPVs (Zäh, et al. 2006).

An overview of 19 models for measuring and evaluating flexibility was provided by Bellmann et al. (2009) in a meta-analysis. They primarily identified the following kinds of models for analyzing flexibility: indicator-based models, models based on available options for decision making, models based on economic target criteria, capacity-oriented models and models of thermodynamics/entropy. After a comparison of these models based on different criteria, they assessed the models based on economic target criteria to be the most informative, as they included an assessment of flexibility potential, not only a measurement (Bellmann et al., 2009).

The above overview of existing methods shows that a few generally applicable methods do exist that are useful for the economic evaluation of actions intended to increase flexibility. Furthermore, there are various approaches that specifically address the evaluation of flexibility-related actions. Nevertheless, these methods neither consider the specific characteristics of I4.0 nor strictly distinguish between actions that increase the available flexibility and those that reduce the need for flexibility in a company, as suggested in Sect. "Industry 4.0 impact on flexibility." Additionally, a significant evaluation of flexibility-related actions requires the inclusion of many decision-relevant factors (e.g., environmental factors and characteristics of the production processes). When modeling these factors, only some of the flexibility-related approaches forwarded single pieces of advice (e.g., (Azzone und Bertele 1989), (Zäh, et al. 2006)). Therefore, a methodological approach is needed that can evaluate flexibility-enhancing I4.0 actions while integrating the approaches explained earlier.

Methodological Approach for Assessing Flexibility-Influencing Industry 4.0 Activities

In this part of the paper, a methodological approach is proposed for assessing the economic consequences of the use of I4.0 technological concepts to enhance flexibility. We used an existing generic decision-theory-based procedure model that has been proven to enable a systematic and transparent assessment of complex decision alternatives (Götze et al., 2010b, 2012; Höse & Götze, 2019). Particularly, this procedure model allows for the integrated application of a variety of analysis, forecasting and evaluation methods, and may serve as a means of communication. This study adapted and tailored this generic procedure model toward the subject of flexibility-influencing I4.0 activities based on their conceptualization in Sect. "Industry 4.0 impact on flexibility" and the literature review presented in Sect. "Overview of existing approaches."

The steps of the procedure model are aligned to the basic elements of decision models according to decision theory. Therefore, they include the following:

- The systematic elaboration of the target system;
- The analysis and forecasting of environmental factors or scenarios that raise the need for flexibility and influence the results of I4.0 activities;
- The elaboration of alternatives, i.e., the actions involved in the use of I4.0 technological concepts to enhance flexibility;
- The determination and application of result functions that show which consequences and outcomes of the target figure result from the alternatives and the environmental states (Bamberg et al., 2019).

Figure 4 shows the steps of the model.

Step 0 (S0) consists of the determination of the goal(s) and scope of a given study. Here, it is assumed that a flexibility-related problem (e.g., increasing product

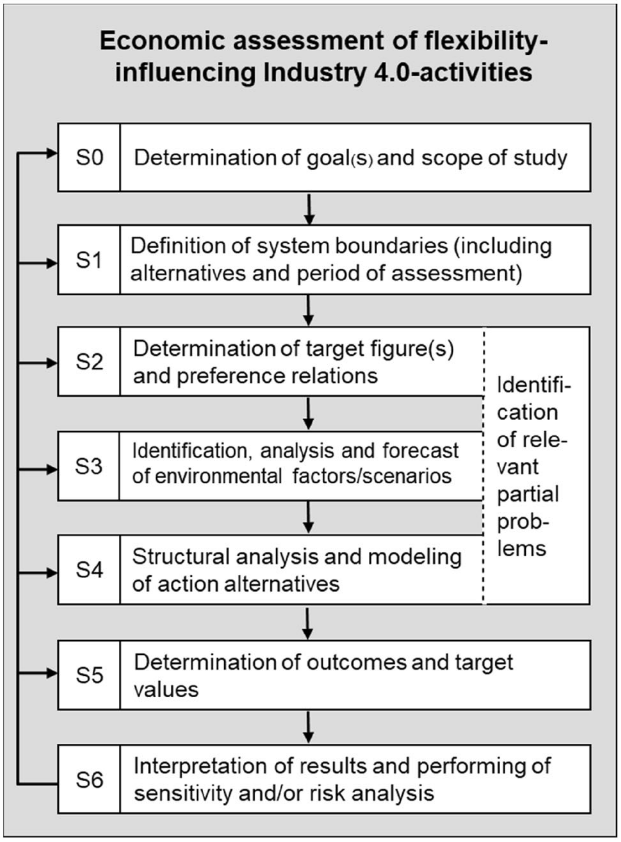

Fig. 4 Decision-theory-based procedure model (based on Götze et al., 2010b, 2012; Höse & Götze, 2019)

variability or fluctuating demand) shall be solved by implementing an I4.0 technology in a manufacturing company. The goal of this study is to assess the economic profitability of realizing an I4.0 technological concept concretized by specific objects such as sensors, robots, and cloud solutions (see Sect. "Industry 4.0 impact on flexibility") that influence input, throughput, and/or output flexibility (see Sect. "Flexibility and its role in manufacturing systems" and "Industry 4.0 impact on flexibility"). Through this, the systematic selection of one or more technological concepts takes place. Additionally, the scope of a given study regarding the (part of the) manufacturing system under consideration—a single manufacturing process, a process chain, the whole manufacturing process of a company or even a whole supply chain—needs to be determined.

Next, this scope is specified by defining the system boundaries (S1). These comprise the following:

- The target figures;
- The environmental factors;
- The alternatives;
- The effects of the alternatives;
- The time frame of the study (Götze et al., 2014).

Concerning the target figures, a decision has to be made as to whether monetary figures and/or non-monetary figures are to be included. This depends on the flexibility-related target system of a given company (see Sect. "Flexibility and its role in manufacturing systems") and the availability of data. Regarding the environmental factors, those that are most important to the need for flexibility and the profitability of the alternatives must be identified to delimit the relevant environmental system (e.g., markets and their volume/growth, the competitive structure, prices of technology solutions, etc.). With respect to the alternatives, the manufacturing system under consideration may need to be concretized. Furthermore, regarding the existing flexibility-related problem, it has to be specified which I4.0 technological concept (s) are seen as possible solutions to the problem and therefore shall be elaborated and evaluated. Additionally, first configurations of the alternatives may be necessary for the following steps (e.g., processes carried out or supported by different I4.0 technological concepts). Further, in close connection with the included target figures, the relevant types of results have to be defined as well. Finally, the time frame of the analysis needs to be determined. When making this decision, the life cycles of the technological solution and the products as outputs of the manufacturing system, the length of time of the relevant effects and the ability to forecast these effects should be considered (for arguments to include a life cycle perspective for evaluating CPS as a technical enabler for I4.0, see Höse & Götze, 2019).

Step 2 (S2) focuses on the determination of target figure(s) and preference relations. Here, the concrete target figures are basically dependent on the choice between a monetary and/or non-monetary system of targets (see S1). Monetary target figures directly refer to the initial targets of a company (see Sect. "Flexibility and its role in manufacturing systems"). In the case of monetary figures, profit is an adequate target figure in a short-term perspective, while the NPV is suggested for long-term evaluation (see Sect. "Overview of existing approaches"). If monetary target figures cannot be used (e.g., because of missing data) or not all relevant effects can be recorded in monetary terms, target figure(s) for a non-monetary assessment need to be defined as a substitute or an addition. These can include many supporting targets and flexibility sub-targets, as distinguished in Sect. "Flexibility and its role in manufacturing systems"; they have, therefore, an indirect influence on the initial targets. The non-monetary targets can be structured and aggregated in either a checklist or utility value analysis, as described in Sect. "Overview of existing approaches." Consequently, the system of target figures can consist of one or more monetary targets only, non-monetary targets only, or a combination of monetary and non-monetary target figures. In the case of there being more than one target figure (e.g., different non-monetary target figures), it is necessary to state a preference relation regarding the types of target figures (Bamberg et al., 2019). Therefore, the relations between target figures need to be analyzed in detail to detect if they are complementary, indifferent (a change in one target figure has no influence on another target figure) or adversarial (Bamberg et al., 2019). In all these cases, preference relations are necessary to indicate the relevance of the different target figures and their outcomes for the decision maker. Additionally, time-related preference relations are needed in dynamic models with outcomes of target figures at different times (Bamberg et al., 2019; Götze et al., 2015). Finally, preference relations are necessary for the valuation of uncertain outcomes of target figures, which are characteristic of flexibility-related decision problems.

In step 3 (S3), the identification, analysis, and forecast of relevant environmental factors take place. Based on decision theory, environmental factors are understood as factors that influence target fulfillment but which are not part of the alternatives under consideration (Bamberg et al., 2019). In line with this definition, these factors comprise company-external factors (e.g., market prices and customer demand) as well as internal factors (e.g., the available resources) (Götze et al., 2014). In general, such factors determine the profitability of alternatives in a variety of ways. Specifically, in the context of flexibility-related decisions about a manufacturing system, they determine the uncertainty of the environment that leads to the need for flexibility in the system. Therefore, the relevant environmental factors that either influence the need for flexibility and/or affect the profitability of the alternatives under consideration have to be identified, analyzed, and forecast to create a basis for the modeling of the manufacturing system, the flexibility needed in the system, alternative system configurations (including the use of I4.0 technologies) and the flexibility provided by them, as well as the target achievement in the following steps. Various forecasting techniques can be applied in this stage. In particular, the scenario method is useful for illustrating the spectrum of the possible developments of the environmental factors (Gerpott, 2005; Götze et al., 2014) that are the source of the needed flexibility. If risk analysis—understood as a method of investment appraisal under uncertainty (see Sect. "Overview of existing approaches")—is used to include uncertainty, the probability distributions of the uncertain environmental factors must be determined.

The structural analysis and modeling of the (flexibility-related) alternatives are carried out in the next step (S4). This comprises a description of the manufacturing system that characterizes its resources, such as machines (inputs), its operational processes and information flows (processes), and its products (outputs) for the cases of using and not using I4.0 technologies. Additionally, the needed and available input, throughput, and output flexibility (resource, process, and product flexibility; see Sect. 2 of the alternative (I4.0-technology-dependent) manufacturing system configurations, are analyzed. The aim is to model the (expected) situations before and after a flexibility-changing I4.0 action is implemented in order to provide a basis for the following evaluation steps and to determine how the I4.0 technological concept(s) affect(s) a given manufacturing system and its flexibility.

Regarding the actions to be modeled and evaluated, a number of different cases have to be distinguished, since these have consequences for the analysis and modeling. These are shown in the following morphological box.

In a specific decision situation, for each criterion except the last only one of these outcomes will be relevant; for the last outcome (technological concept), more than one can be relevant. The criteria have the following consequences for the modeling task (see Table 2):

- *Number of I4.0 alternatives* In the case of one I4.0 alternative, its absolute profitability has to be evaluated by comparing it with the alternative of not using I4.0. If some I4.0 technological options are available and promising, they all have to be assessed to identify those which are relatively profitable. (For the concepts of absolute and relative profitability, see Götze et al., 2015.)
- *Time frame* The time frame and the corresponding length of the planning and assessment period influence the way in which time should be modeled, e.g., with one single time period (static model) or different periods that are explicitly distinguished in the model (dynamic model). Therefore, different target figures can be adequate (e.g., profit and utility value in static models and net present value in dynamic models) (see step 2 (Götze et al., 2015)).
- *Effect on flexibility* If an I4.0 technology only affects the need for flexibility (e.g., the e-value chain), either the as-is-manufacturing-system (the existing process chain) and/or alternative system (process chain) configurations have to be modeled with respect to the new need for flexibility. In cases where the available flexibility is influenced, e.g., by cloud solutions, sensors, or autonomous robots, the existing and new process chains have to be modeled (against the background of a given need for flexibility). The same holds true for cases where needed as well as available flexibility are influenced.
- *Affected processes* According to this criterion, operational and/or information processes (flows) have to be modeled.

Table 2 Morphological box of alternative-related decision situations

<table>
<tr><th>Criterion</th><th colspan="8">Outcomes</th></tr>
<tr><td>Number of I4.0 alternatives</td><td colspan="5">One</td><td colspan="3">More than one</td></tr>
<tr><td>Time frame</td><td colspan="5">Short-term</td><td colspan="3">Long-term</td></tr>
<tr><td>Effect on flexibility</td><td colspan="4">Need for flexibility</td><td colspan="2">Available flexibility</td><td colspan="2">Need for and available flexibility</td></tr>
<tr><td>Affected processes</td><td colspan="6">Operational processes</td><td>Information processes</td><td>Operational and information processes</td></tr>
<tr><td>Technological concepts</td><td>AM</td><td>Cloud</td><td>MES</td><td>IoT & CPS</td><td>Data Analytics</td><td>Sensors</td><td>E-value Chain</td><td>Autonomous Robots</td></tr>
</table>

- *Technological concepts* The relevant technological concepts and their characteristics—as described in Sect. "Industry 4.0 impact on flexibility" (Table 1)—imply the methods and extent of changes in processes and the respective detailed models.

To showcase the relevance of the presented morphological table as a practical, ready-to-use tool, two different examples are presented below that address each above-described dimension and the type of flexibility impact outlined in Sect. "Industry 4.0 impact on flexibility."

The first example concerns only one technological concept: A company plans to implement sensors to increase their available level of flexibility in terms of the product output of an existing production line.

The company produces standard coffee capsules through plastic injection molding, but it wants to extend its business into the premium coffee capsules market. This latter type stands out from the standard capsule type in two ways: the capsules have more complex geometries (small thickness), and they can be made out of biomaterials. Although the existing molds are equipped with sensors, these do not have the precision needed to produce the premium capsules. Furthermore, the consumer will be responsible for filling the capsules with coffee and the company knows that this will be carried out automatically by a filling machine—the quality of the final product is thus paramount. Therefore, different molds have to be acquired, but more than this, different types of sensors have to be used to equip such molds in order to guarantee more control and adjustment in the injection process. The company is only considering a single I4.0 alternative to solve this purely operational challenge. The mentioned sensors will be set up to impact the short-term available level of the flexibility of this production line; that is, the implementation of such sensors will allow the company to start producing new products that require a higher degree of flexibility than currently exists in the manufacturing system—in this case, the products are more sophisticated molds. In conclusion, the business process model and the company business would encompass a wider range of final products by implementing this one I4.0 alternative (the morphological table for this example can be seen in Annex, Table 3).

The second example deals with a similar company as in the first example, but one that aims to enhance its flexibility through the implementation of not only one, but three I4.0 technological concepts (see Annex, Table 4): the sensor, IoT and CPS, and cloud concepts.

The company is looking for ways to reduce the level of uncertainty inherent to their perception of the coffee capsule market so that it can produce more target products for their costumers—here we are looking at the impact on the necessary level of flexibility (please keep Figs. 2 and 3 in mind for the example that follows). Ubiquitous IoT equipment (sensors and underlying communication platforms) that can be integrated into customers' products (either the company's final products or the customers' own smart products) enable the company to establish direct contact with its customers, regardless of the company's position in the value chain. The cloud might provide a channel for customers to interact with the company through, for example, chatbots, complaint file management, customer surveys, CRM, and other means. This way, the company might acquire target information about the types of products that their customers want, but most importantly, do not want. From another standpoint, the cloud is also a place to store and analyze data on the company itself.

Considering the company in the first example, the following is a clear example of the above-described reasoning. The premium coffee capsules have different geometries and are made of several different biomaterials.

Naturally, their demand needs to be anticipated and their production needs to be planned. To cope with this uncertainty, the company has stocks (and safety stocks) of the materials and stocks of the final products. One problem with keeping stocks is their inherent storage cost. If, however, the company has access to their customers' present/future needs through, for example, the cloud, and knows that their final customers are no longer buying a variety of final products, the company can then stop purchasing a specific type of material and halt its production of a certain product, freeing up the manufacturing process for other products. In this way, the company is reducing its level of necessary flexibility through access to various types of information. This single I4.0 alternative, which encompasses three technological concepts, addresses information and operational processes that impact both the available short-term level of flexibility (such as in the previous example) and the long-term necessary level of flexibility, since it can anticipate demand to plan production more efficiently. The key here is for the company to be able to adjust its necessary level of flexibility according to its available level of flexibility in the most effective way permitted by the nexus of technology and the external entities' capabilities.

For analysis and modeling, several existing methods can be applied in a specified way. These include the Supply Chain Operations Reference model (Bolstorff & Rosenbaum, 2003) and the Value Stream Mapping (Singh et al., 2011) for the modeling and analysis of process chains. For the modeling of single processes or process steps, it is suggested that the I–T–O model should be used—but now not on a generic level (such as in Sects. "Flexibility and its role in manufacturing systems" and "Industry 4.0 impact on flexibility") but rather in a far more concrete and detailed way that reflects the needed and available flexibility (measured by indicators), as well as the different types of inputs, throughput parameters (including production cycles) and outputs that depend on flexibility. Instruments such as measurements, simulation, and process-based cost models can be applied in the frame of the I–T–O model or independently from it. If information flows have to be included, relevant information modeling techniques, such as data flow diagrams (Wieringa, 2003), may be useful.

Based on the insights derived from the detailed analyses and forecasts in steps 3 and 4, so-called result functions have to be constructed to determinate the outcomes and the corresponding target figure values (S5). These target values need to be calculated for every alternative—they are the basis for decision making (Götze et al., 2014). For evaluating and comparing the alternatives, only the aspects that differ between the alternatives have to be considered.

The result functions are dependent on the target figures defined in step 2. Firstly, these target figures imply calculation methods, such as the net present value method and utility value analysis, that constitute a frame for the result functions. Secondly, the parameters that have to be included in the result functions depend on the target figures: For the net present value method, they comprise cash inflows and cash outflows and their elements; for utility value analysis, they include the outcomes of indicators/target figures, the partial utility values that result from them and the weightings for target criteria that reflect the preference relation (Götze et al., 2015).

Since flexibility is inevitably connected with uncertainty (being a reason flexibility is needed), the target figures necessarily have to be calculated against the background of uncertainty. In the case of the net present value method, an expected net present value can be calculated from the net present values that are computed for different environmental scenarios multiplied by the probabilities of the scenarios. In the case of utility value analysis, either an expected utility value can be calculated (analogous to the net present value method) or the quality of "managing" uncertainty by consciously managing flexibility is reflected by the target figures included in the analysis. In the case of conducting risk analysis, a distribution of target figures has to be calculated by simulation.

As the decision problems under consideration usually are quite complex, uncertainty has a major influence, and many assumptions have to be made, it is suggested to apply sensitivity analyses, as described in the beginning of Sect. "Assessment of flexibility and flexibility-related measures" (S6). This supports the interpretation of the results, as the most relevant influencing factors, critical values of the influencing factors and consequences of potential deviations can be identified (Götze et al., 2014). The interpretation of the results is twofold—statements regarding the influence of the alternative on either the input, throughput, and output flexibility or the overall economic impact can be made. If risk analysis is used, both methods can be used in a combined approach.

Although the procedure model consists of steps that follow each other, these are connected by information flows as well as feedback loops, so that the information in a later step can have consequences for an earlier one. Additionally, it is possible to identify sub-assessment tasks resulting from partial problems. (For a detailed description of the possibilities of the decomposition of the main problem in partial problems, see (Götze, et al. 2014).)

Discussion and Conclusions

The management and control of manufacturing flexibility is a major challenge for many industrial companies. I4.0 appears to have the potential to assist in responding to this challenge. This paper contributes to two fields of the vast I4.0 literature and to the body of knowledge and methods that is available for manufacturing companies.

First, it focused on the contributions of the different I4.0 technologies and analyzed their possible impact on the available and needed manufacturing flexibility of a given company. By referring to this differentiation and investigating whether, and if so, how different I4.0 technological concepts influence both dimensions of manufacturing flexibility, the paper provides a more comprehensive understanding of the potential of I4.0 with regard to flexibility. This theoretical contribution should assist future work concerning the systematic control of manufacturing flexibility and especially the balance between available and needed manufacturing flexibility, among other factors. Practitioners can use the generated scheme of the relationships between I4.0 technological concepts and flexibility as a starting point for an analysis of a company´s flexibility status, as well as the identification of actions for its improvement. However, some limitations of the study and its results have to be noted. Above all, the relationships between I4.0 technological concepts and available and needed flexibility have only been analyzed on a quite generic level—an in-depth analysis of each identified impact was not able to be realized due to the restricted scope of the paper. Additionally, while the analyses performed above considered each isolated technological concept, future research should focus on their combination and how this may change their impacts on manufacturing flexibility.

Second, the paper contributes to the methodology of the economic assessment of actions for implementing I4.0 concepts with a specific focus on flexibility. Firstly, a literature overview was provided, which included generally applicable methods as well as flexibility-specific approaches. Second, our own methodological approach was suggested, which tailors an existing decision-theory-based procedure model to enable a systematic assessment of the profitability of investments in I4.0 technologies. Scientists can use this approach for the further development of the evaluation methodology. Further, it can be used in studies on the economic advantages of I4.0 technological concepts with regard to flexibility. Additionally, practitioners can use the approach as a means for evaluating the economic profitability of concrete flexibility-influencing actions.

Again, some limitations of the study and its results have to be mentioned. The suggested methodological approach does not fully overcome the inherent challenges of assessing concepts and actions that aim to control manufacturing flexibility through the use of I4.0 technologies. One basic reason for this caveat is the origin of the need for flexibility—uncertainty. Usually, uncertainty cannot be measured precisely, but rather only subjectively estimated. This implies that the data describing uncertainty in any given model are also uncertain ("uncertainty about uncertainty"). Therefore, the outcomes of the application of the proposed procedure model should be interpreted carefully—they are the result of models that simplify reality in general and especially with respect to existing uncertainty. In the case of I4.0 technologies, this challenge is enhanced by the variety of existing I4.0 technologies that exist, their possible design options and the lack of available case studies, experience, and information about their performance. To limit the negative effects of a restricted database and the ultimately unresolvable "uncertainty about uncertainty," the careful and intensive provision of data and knowledge management approaches, as well as the use of scenarios and sensitivity analysis, is recommended. Additionally, the needed and available flexibility of a given company, as well as the performance of I4.0 technologies, should be repeatedly estimated and evaluated in adequate control cycles. A further limitation is that the suggested methodological approach has not been specified for the multitude of possible short-term and long-term decision situations of different I4.0 technologies, as well as for the types of flexibility—implying that further specification is needed. Finally, the approach has not been applied to a use case until now. Therefore, its applicability and usefulness has not been proven in the flexibility context.

The paragraphs above indicate the need for further research. On the one hand, with regard to the conceptualization presented in Sect. "Industry 4.0 impact on flexibility," an in-depth analysis of the individual impacts of I4.0 technological concepts on the available and needed flexibility of a company should be conducted in particular. On the other hand, our own proposed methodological approach should be further developed. This would involve searching for data provision and forecasting approaches that are able to generate an adequate database for economic evaluation against the backdrop of uncertainty about uncertainty. Furthermore, the methodological approach should be specified with regard to different I4.0 technologies and types of flexibility. Finally, case study research may provide insights about the applicability and usefulness of such an approach.

Appendix

See Tables 3 and 4.

Table 3 Morphological box for the example of sensor implementation

<table>
<tr><th>Criterion</th><th colspan="8">Outcomes</th></tr>
<tr><td>Number of I4.0 alternatives</td><td colspan="5">One</td><td colspan="3">More than one</td></tr>
<tr><td>Time frame</td><td colspan="5">Short-term</td><td colspan="3">Long-term</td></tr>
<tr><td>Effect on flexibility</td><td colspan="3">Need for flexibility</td><td colspan="3">Available flexibility</td><td colspan="2">Need for and available flexibility</td></tr>
<tr><td>Affected processes</td><td colspan="5">Operational processes</td><td>Information processes</td><td colspan="2">Operational and information processes</td></tr>
<tr><td>Technological concepts</td><td>AM</td><td>Cloud</td><td>MES</td><td>IoT & CPS</td><td>Data Analytics</td><td>Sensors</td><td>E-value Chain</td><td>Autonomous Robots</td></tr>
</table>

Table 4 Morphological box for the example of the implementation of two or more I4.0 technological concepts

<table>
<tr><th>Criterion</th><th colspan="8">Outcomes</th></tr>
<tr><td>Number of I4.0 alternatives</td><td colspan="5">One</td><td colspan="3">More than one</td></tr>
<tr><td>Time frame</td><td colspan="5">Short-term</td><td colspan="3">Long-term</td></tr>
<tr><td>Effect on flexibility</td><td colspan="3">Need for flexibility</td><td colspan="3">Available flexibility</td><td colspan="2">Need for and available flexibility</td></tr>
<tr><td>Affected processes</td><td colspan="5">Operational processes</td><td>Information processes</td><td colspan="2">Operational and information processes</td></tr>
<tr><td>Technological concepts</td><td>AM</td><td>Cloud</td><td>MES</td><td>IoT & CPS</td><td>Data Analytics</td><td>Sensors</td><td>E-value Chain</td><td>Autonomous Robots</td></tr>
</table>

Acknowledgements The publication of this article was funded by the Chemnitz University of Technology. The work was supported by FCT, through IDMEC, under LAETA, project UIDB/50022/2020. The authors gratefully acknowledge the funding of Project POCI-01–0247-FEDER-046102, co-financed by Programa Operacional Competitividade e Internacionalização and Programa Operacional Regional de Lisboa, through Fundo Europeu de Desenvolvimento Regional (FEDER) and by National Funds through FCT—Fundação para a Ciência e Tecnologia.

Author contributions UG, AA, PP, and KH contributed to idea for the article and writing and critical revision, and AA and KH were involved in literature search and data analysis.

Funding Open Access funding enabled and organized by Projekt DEAL. The authors declare they have no financial interests.

Declarations

Conflicts of interest The authors declare no conflict of interest.

References

Ali, M. (2012). Impact of routing and pallet flexibility on flexible manufacturing system. *Global Journal of Flexible Systems Management, 13*, 141–149. https://doi.org/10.1007/s40171-012-0016-3

Ali, M., & Mohd, M. (2016). Performance evaluation of flexible manufacturing system under different material handling strategies. *Global Journal of Flexible Systems Management, 17*, 287–305. https://doi.org/10.1007/s40171-016-0127-3

Amaral, A., & Peças, P. (2021a). SMEs and Industry 4.0: Two case studies of digitalization for a smoother integration. *Computers in Industry, 125*, 103333. https://doi.org/10.1016/j.compind.2020.103333

Amaral, A., & Peças, P. (2021b). A Framework for Assessing manufacturing SMEs industry 4.0 maturity. *Applied Sciences, 11*(13), 6127. https://doi.org/10.3390/app11136127

Azzone, G., & Bertelé, U. (1989). Measuring the economic effectiveness of flexible automation: A new approach. *International Journal of Production Research, 27*, 735–746. https://doi.org/10.1080/00207548908942583

Bamberg, G., Coenenberg, A. G., & Krapp, M. (2019). *Betriebswirtschaftliche Entscheidungslehre*. Verlag Franz Vahlen GmbH.

Bellmann, K., Himpel, F., & Böhm, A. (2009). Messung von flexibilität in der produktion. In J. Stohhecker & A. Größler (Eds.), *Strategisches und operatives Produktionsmanagement* (pp. 221–240). Gabler Verlag.

Bibby, L., & Dehe, B. (2018). Defining and assessing industry 4.0 maturity levels–case of the defence sector. *Production Planning and Control, 29*, 1030–1043. https://doi.org/10.1080/09537287.2018.1503355

Bolstorff, P., & Rosenbaum, R. (2003). *Supply Chain Excellence: A Handbook for Dramatic Improvement Using the SCOR Model*. AMACOM.

Brettel, M., Bendig, D., Keller, M., et al. (2014). Effectuation in manufacturing: How entrepreneurial decision-making techniques can be used to deal with uncertainty in manufacturing. *Procedia CIRP, 17*, 611–616. https://doi.org/10.1016/j.procir.2014.03.119

Browne, J., Dubois, D., Rathmill, K., et al. (1984). Classification of Flexible Manufacturing Systems. *The FMS Magazine, 2*, 114–117.

Castro-Martin, A. P., Ahuett-Garza, H., Guamán-Lozada, D., Márquez-Alderete, M. F., Urbina, P. D., Coronado, P. A., Castañon, O., Kurfess, T. R., González, E., & de Castilla,. (2021). Connectivity as a design feature for industry 4.0 production equipment: Application for the development of an in-line metrology system. *Applied Sciences, 11*(3), 1312. https://doi.org/10.3390/app11031312

Cingöz, A., & Akdoğan, A. A. (2013). Strategic flexibility, environmental dynamism, and innovation performance: An empirical study. *Procedia-Social and Behavioral Sciences, 99*, 582–589. https://doi.org/10.1016/j.sbspro.2013.10.528

Contador, J. C., Satyro, W. C., Contador, J. L., de Spinola, M., & M,. (2020). Flexibility in the Brazilian industry 4.0: Challenges and opportunities. *Global Journal of Flexible Systems Management, 21*, 15–31. https://doi.org/10.1007/s40171-020-00240-y

Corrêa, HL. (1992). The Links Between Uncertainty, Variability of Outputs and Flexibility in Manufacturing Systems. Doctoral dissertation, University of Warwick

De Toni, A., & Tonchia, S. (1998). Manufacturing flexibility: A literature review. *International Journal of Production Research, 36*, 1587–1617.

Enrique, D. V., Marcon, É., Charrua-Santos, F., & Frank, A. G. (2022). Industry 4.0 enabling manufacturing flexibility: Technology contributions to individual resource and shop floor flexibility. *Journal of Manufacturing Technology Management, 33*, 853–875. https://doi.org/10.1108/JMTM-08-2021-0312

Erol, S., Schumacher, A., & Sihn, W. (2016). Strategic guidance towards industry 4.0-a three-stage process model. *International Conference on Competitive Manufacturing, 9*(1), 495–501.

Fernandes, J., Reis, J., Melão, N., Teixeira, L., & Amorim, M. (2021). The role of industry 4.0 and BPMN in the arise of condition-based and predictive maintenance: a case study in the automotive industry. *Applied Sciences, 11*(8), 3438. https://doi.org/10.3390/app11083438

Fuhrmann, B. (1998). *Prozeßmanagement in kleinen und mittleren Unternehmen*. Gabler Verlag.

Gerpott, T. J. (2005). *Strategisches Technologie- und Innovationsmanagement*. Schäffer-Poeschel.

Götze, U., Helmberg, C., Rünger, G., et al. (2010a). Integrating energy flows in modeling manufacturing processes and process chains of powertrain components. In: Neugebauer R (ed) Energieeffiziente Produkt- und Prozessinnovationen in der Produktionstechnik – Tagungsband zum 1. Internationalen Kolloquium des Spitzentechnologieclusters eniPROD. Chemnitz, pp. 409–437

Götze, U., Schmidt, A., Symmank, C., et al. (2014). Zur Analyse und Bewertung von Produkt-Prozessketten-Kombinationen der hybriden Produktion. In: Neugebauer R, Götze U, Drossel W-G (eds) Energetisch-wirtschaftliche Bilanzierung - Diskussion der Ergebnisse des Spitzentechnologieclusters eniPROD: 3. Methodenband der Querschnittsarbeitsgruppe "Energetisch-wirtschaftliche Bilanzierung" des Spitzentechnologieclusters eniPROD. Auerbach, pp. 21–32

Götze, U., Hache, B., Schmidt, A., & Weber, T. (2011). Methodik zur kostenorientierten Bewertung von Prozessketten der Werkstoffverarbeitung. *Materialwissenschaft Und Werkstofftechniktechnik, 42*, 647–657.

Götze, U., Koriath, H.-J., Kolesnikov, A., et al. (2012). Integrated methodology for the evaluation of the energy- and cost-effectiveness of machine tools. *CIRP Journal of Manufacturing Science and Technology, 5*, 151–163. https://doi.org/10.1016/j.cirpj.2012.04.001

Götze, U., Northcott, D., & Schuster, P. (2015). *Investment Appraisal–Methods and Models*. Springer.

Götze, U., Schmidt, A., & Weber, T. (2010b). Vorgehensmodell zur Abbildung und Analyse des Lebenszykluserfolges von Werkstoffen - Konzeption und beispielhafte Veranschaulichung. Modeling approach for the life cycle profit of materials-conceptual design and case study. *Materwiss Werksttech, 41*, 464–475. https://doi.org/10.1002/mawe.201000628

Heinen, E. (1990). *Industriebetriebslehre: Entscheidungen im Industriebetrieb*. Gabler Verlag.

Helo, P., Suorsa, M., Hao, Y., & Anussornnitisarn, P. (2014). Toward a cloud-based manufacturing execution system for distributed manufacturing. *Computers in Industry, 65*, 646–656. https://doi.org/10.1016/j.compind.2014.01.015

Hopkinson, M. (2017). *Net Present Value and Risk Modelling for Projects*. Taylor and Francis.

Höse, K., Götze, U. (2019). Life cycle-oriented evaluation of cyber-physical systems. IoTBDS 2019: Proceedings of the 4th International Conference on Internet of Things, Big Data and Security, p 332–338

Jacob, H. (1989). Flexibilität und ihre Bedeutung für die Betriebspolitik. In D. Adam, K. Backhaus, H. Meffert, & H. Wagner (Eds.), *Integration und Flexibilität – Eine Herausforderung für die Allgemeine Betriebswirtschaftslehre* (pp. 15–60). Gabler Verlag.

Jain, V., & Raj, T. (2013). Ranking of flexibility in flexible manufacturing system by using a combined multiple attribute decision making method. *Global Journal of Flexible Systems Management, 14*, 125–141. https://doi.org/10.1007/s40171-013-0038-5

Javaid, M., Haleem, A., Singh, R. P., & Suman, R. (2022). Enabling flexible manufacturing system (FMS) through the applications of industry 4.0 technologies. *Internet of Things and Cyber-Physical Systems, 2*, 49–62. https://doi.org/10.1016/j.iotcps.2022.05.005

Kumar, V., Vrat, P., & Shankar, R. (2022). Factors influencing the implementation of industry 4.0 for sustainability in manufacturing. *Global Journal of Flexible Systems Management,* 23(4), 453–478.

Lasi, H., Fettke, P., Kemper, H. G., et al. (2014). Industry 4.0. *Business and Information Systems Engineering, 6*, 239–242. https://doi.org/10.1007/s12599-014-0334-4

LaValle, S., Lesser, E., Rebecca, S., et al. (2011). Big data, analytics and the path from insights to value. *MIT Sloan Management Review, 52*, 21–22.

Lichblau, K., Stich, V., Bertenrath, R., et al. (2015). Industrie 4.0-Readiness. Technical report, VDMA Impuls-Stiftung für den Maschinenbau, den Anlagenbau und die Informationstechnik, Frankfurt am Main

Long, F., Zeiler, P., & Bertsche, B. (2017). Modelling the flexibility of production systems in industry 4.0 for analysing their productivity and availability with high-level Petri nets. *IFAC-PapersOnLine, 50*, 5680–5687. https://doi.org/10.1016/j.ifacol.2017.08.1118

Mascarenhas, B. (1981). Planning for flexibility. *Long Range Planning, 14*, 78–82. https://doi.org/10.1016/0024-6301(81)90011-X

McAfee, A., Brynjolfsson, E. (2012). Big data-the management revolution. *Harverd Business Review*, *90*, 60-6, 68, 128

Merchant, M. E. (1983). Current status of, and potential for, automation in the metalworking manufacturing industry. *CIRP Annals, 32*, 519–524. https://doi.org/10.1016/S0007-8506(07)60178-4

Mikus, B. (2009). Make-or-buy-Entscheidungen - Führungsprozesse, Risikomanagement und Modellanalysen. GUC – Verlag der Gesellschaft für Unternehmensrechnung und Controlling m. b. H., Chemnitz

Mishra, R., Pundir, A. K., & Ganapathy, L. (2014). manufacturing flexibility research: A review of literature and agenda for future research. *Global Journal of Flexible Systems Management, 15*, 101–112. https://doi.org/10.1007/s40171-013-0057-2

Pessl, E., Sorko, SR., Mayer, B. (2020). Roadmap industry 4.0-Implementation guideline for enterprises. In: 26th International Association for Management of Technology Conference, IAMOT 2017. International Association for Management of Technology Conference (IAMOT) and the Graduate School of Technology Management, University of Pretoria, pp 1728–1743

Rocky Newman, W., Hanna, M., & Jo Maffei, M. (1993). Dealing with the uncertainties of manufacturing: flexibility, buffers and integration. *International Journal of Operations & Production Management, 13*, 19–34. https://doi.org/10.1108/01443579310023972

Saenz de Ugarte, B., Artiba, A., & Pellerin, R. (2009). Manufacturing execution system—A literature review. *Production Planning & Control, 20*, 525–539. https://doi.org/10.1080/09537280902938613

Saha, P., Talapatra, S., Belal, H. M., & Jackson, V. (2022). Unleashing the Potential of the TQM and Industry 4.0 to Achieve Sustainability Performance in the Context of a Developing Country. *Global Journal of Flexible Systems Management*, 23(4), 495–513.

Sajjad, A., Ahmad, W., Hussain, S., & Mehmood, R. M. (2022). Development of innovative operational flexibility measurement model for smart systems in industry 4.0 paradigm. *IEEE Access, 10*, 6760–6774. https://doi.org/10.1109/ACCESS.2021.3139544

Salunkhe, O., & Berglund, Å. F. (2022). Industry 4.0 enabling technologies for increasing operational flexibility in final assembly. *International Journal of Industrial Engineering and Management, 13*(1), 38–48. https://doi.org/10.24867/IJIEM-2022-1-299

Santos, R. C., & Martinho, J. L. (2019). An industry 4.0 maturity model proposal. *Journal of Manufacturing Technology Management, 31*, 1023–1043. https://doi.org/10.1108/JMTM-09-2018-0284

Sassanelli, C., & Terzi, S. (2022). The D-BEST reference model: a flexible and sustainable support for the digital transformation of small and medium enterprises. *Global Journal of Flexible Systems Management*, 23(3), 345–370.

Sawhney, R. (2006). Interplay between uncertainty and flexibility across the value-chain: Towards a transformation model of manufacturing flexibility. *Journal of Operations Management, 24*, 476–493. https://doi.org/10.1016/j.jom.2005.11.008

Sethi, A. K., & Sethi, S. P. (1990). Flexibility in manufacturing: A survey flexibility in manufacturing: A survey. *International Journal of Flexible Manufacturing Systems, 2*, 289–328. https://doi.org/10.1007/BF00186471

Singh, B., Garg, S. K., & Sharma, S. K. (2011). Value stream mapping: Literature review and implications for Indian industry. *The International Journal of Advanced Manufacturing Technology, 53*, 799–809. https://doi.org/10.1007/s00170-010-2860-7

Solke, N. S., Shah, P., Sekhar, R., & Singh, T. P. (2022). Machine learning-based predictive modeling and control of lean manufacturing in automotive parts manufacturing industry. *Global Journal of Flexible Systems Management*, 23(1), 89–112.

Sushil. (2009). SAP-LAP linkages–a generic interpretive framework for analyzing managerial contexts. *Global Journal of Flexible Systems Management*, 10(2), 11–20.

Targowski, A. (2014). From data to wisdom. *Dialogue and Universalism, 15*, 55–71. https://doi.org/10.5840/du2005155/629

Thielen, CAL. (1993). Management der Flexibilität: Integriertes Anforderungskonzept für eine flexible Gestaltung der Unternehmung. Difo-Druck GmbH, Bamberg

Vahs, D. (2014). Entwicklung einer Geschäftsidee. In: BWL-Wissen zur Existenzgründung. Berliner Wissenschafts-Verlag, Berlin

Wadhwa, S., Singholi, A., & Ali, M. (2010). Evaluating the Effect of Part-mix and Routing Flexibility on FMS Performance. *Global Journal of Flexible Systems Management, 11*, 17–23. https://doi.org/10.1007/BF03396591

Wieringa, R. J. (2003). Data flow diagrams. *Design Methods for Reactive Systems* (pp. 185–200). Elsevier. https://doi.org/10.1016/B978-155860755-2/50022-8

Zäh, MF., Moeller, N., Muessig, B., Rimpau, C. (2006). Life cycle oriented valuation of manufacturing flexibility. In: Proceedings of the 13th CIRP International Conference on Life Cycle Engineering, LCE pp. 699–704

Key Questions

1. What is the role of flexibility in manufacturing systems?
2. What is the relationship between I4.0 technological concepts and flexibility on a conceptional level?
3. How can economic consequences of flexibility-changing activities be evaluated?

Kristina Höse is a member of the Chair of Management Accounting and Control since 2017. Her main research topics refer to the sustainability-related evaluation of Industry 4.0 technologies as well as business models. Additionally, Kristina Höse gives lectures in the area of controlling, management accounting and operative corporate management.

Afonso Amaral is a mechanical engineer who has been focusing on industrial policy over the past 5 years, and he has specialized in maturity models and implementation of critical technologies in SMEs, their integration in Industry 4.0, and how these companies can shape themselves to reap the full benefits of their inherent digital transformation.

Prof. Dr. Prof. h. c. Uwe Götze is university professor for Management Accounting and Control (Faculty of Economics and Business Administration) as well as Deputy President and Vice President for Transfer and Academic Qualification of Chemnitz University of Technology. He has conducted various research projects concerning life cycle-related economic and environmental evaluation as well as innovation management in different contexts.

Prof. Paulo Peças is associated professor of the Manufacturing Technology and Industrial Management Scientific Area of the Mechanical Department of Instituto Superior Técnico at Universidade de Lisboa. He is also senior researcher of IDMEC, the mechanical engineering institute of LAETA-Associated Laboratory for Energy, Transports and Aeronautics. He has published dozens of publications in scientific journals, books and conference proceeding, as well as coordinate and participate various research projects in the field of life cycle engineering, sustainable production, technology and materials selection models, and lean manufacturing.