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From Complexity To Clarity In Sustainable Factory Planning: A Conceptual Approach For Data-driven Integration Of Green Factory KPIs In Manufacturing Site Selection

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Abstract

The selection of manufacturing facility locations entails high costs and long-term consequences. This necessitates an objective approach to mitigate uncertainties associated with subjective decision-making. Our paper builds upon previous research on data-driven location selection and conceptually extends it to integrate sustainability potential evaluation. By combining Green Factory Key Performance Indicators (KPIs), the authors aim to facilitate and standardize long-term decision-making in sustainable factory planning.

After outlining the requirements, current state of the art, and limitations of location selection, we emphasize the need for integrating region-specific Green Factory KPIs with new data sources for site selection. Therefore, we propose a methodology involving a review of scientific literature and other sources to identify data sources for site selection, establishing research criteria for determining data suitability. The results include suitable subsets for location selection and future steps such as criteria application and target data determination.

This paper contributes to paving the way for implementing sustainability-driven location selection strategies in factory planning. In conclusion, we outline a roadmap for further development and suggest two areas for future research: data collection and integration, as well as developing and validating a location selection app.

Keywords

Factory Planning; Site Selection; Sustainability; Digitalization; Green Factory

1. Motivation

Sustainability and digitalization, among the most significant global megatrends, still need to be sufficiently considered in established factory location selection approaches. This publication aims to demonstrate these gaps and outlines ways to consider them in data research for objective and sustainable factory location selection. The authors' long-term aim is to develop an application for factory location selection. Future publications building on this publication will describe the data selection for analysis and the functionalities of an application that analyses this data (see Figure 1).

The approach of this publication is based on the initial description of the motivation and process for factory location selection. The gaps between state-of-the-art and demands in two factory planning trends (digitalization and sustainability) are analyzed. Strategies to close these gaps are derived, starting with systematic and holistic data research as the first step of factory location selection.

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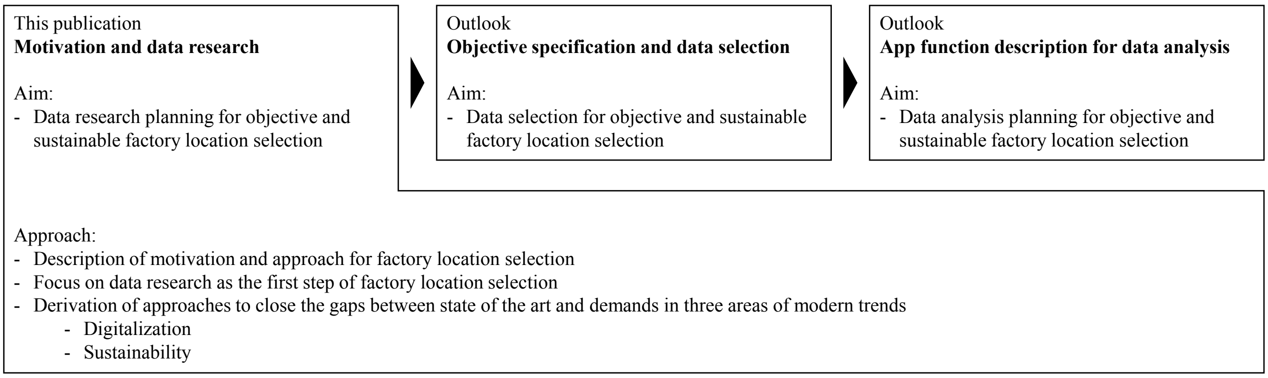

Figure 1. This paper aims to use data research planning as a basis for future research

Two fields of focus are considered in this paper. The first field, digitalization, necessitates and enables new approaches for data research, selection, and analysis for decision support. The second field, green factories, enables new considerations of environmentally sustainable location factors to meet the increasing demand for sustainable production.

2. Factory location selection approach

Factory location selection is crucial for business success. The selection of new factory locations is based on location search and evaluation. This strategic decision is critical in gaining competitive advantages and ensuring operational efficiency for manufacturing companies [1], especially in light of supply shortages, growing market uncertainties, skilled labor shortages, and increasing interconnectedness of production locations [2]. Location selection is a continuous process for most corporations and medium-sized enterprises, with decisions every two years on average [1].

This publication is based on an established approach for factory location selection. In this approach, potential location options are gradually narrowed down: first on a global level, then on a regional level, and finally on a local level. The first step of location selection is the definition of site requirements. These requirements may be derived from the overarching, long-term corporate strategy and the motives for the new site establishment [2]. The second step of the location selection process is the description of possible location alternatives through several location factors. These factors differ depending on the level of planning. [3] This paper builds upon this approach and focuses on location selection from the super-regional to the local level.

This publication focuses on data research since it is a crucial initial step for factory location selection. Location criteria are derived from quantitative and qualitative location factors according to company-specific requirements and can be distinguished into knockout, minimum, and wish criteria. Location selection criteria are selected and weighted differently depending on each case. The location options are either quantitatively or qualitatively evaluated according to these criteria. Quantitative methods mainly calculate expected costs and revenues via net present value [4]. Qualitative methods consider factors not quantifiable in monetary terms primarily via utility analyses and weighted criteria [2]. Quantitative approaches feature the manual selection of alternatives and heuristics or optimizations, enabling automatic decision-making [5]. The most used location selection methods are utility analyses, a qualitative approach [1]. Location selection, therefore, highly depends on the data to be analyzed.

3. Digitalization

Digitalization increases the availability of high-quality data that business decisions need to consider [6]. Decisions must be supported by digital analysis of relevant, high-quality data [7].

The first identified gap (1) lies between the predominant consideration of quantitative factors and the increasing demand for consideration of qualitative factors in location planning. Due to the severe consequences of wrong location selection decisions, they primarily depend on the objective analysis of quantitative information [1]. However, neglecting the systematic consideration of less tangible influencing factors such as political stability or availability of personnel [5] can lead to wrong location selections that are costly or impossible to be reversed later.

The second gap (2) relates to the insufficient number of typically considered influencing factors for strategic decisions [8]. The need for consideration of interconnected location criteria, including emerging dimensions like sustainability [9], calls for a more expansive approach.

The third gap (3) centers around the challenge of identifying and assessing a growing number of factors while simultaneously meeting the demand for more in-depth research, selection, and preparation of these factors. Usually, after matching internal company requirements with specific and weighted location criteria, information is gathered about the locations' external environments for qualitative and quantitative analysis [2]. Hence, data research, selection, and preparation are the basis for any location selection analysis [1].

The fourth gap (4) lies in the increasing complexity and subjectivity in decision-making, necessitating the acceleration of simpler, objective decisions. Established location selection methods need to consider this current complexity [10]. Complexity reduction is necessary for accelerating decisions while ensuring high decision quality for strategic decisions with long-term consequences [11].

The fifth gap (5) lies between current quasi-rational and subjective location decisions, intuitively made by expert teams [8], the demand for uncertainty reduction, and the uncertainty-increasing need for a wider variety of influencing factors. The subjective location decisions are based on uncertain qualitative and quantitative information [12], resulting in long-term, complex, and difficult-to-reverse decisions [9]. Additional information reduces these uncertainties [13].

Closing the first gap (1) requires systematically considering all available and suitable quantitative and qualitative factors in location planning. Examples of such data can be found in the fifth chapter. A guideline is to be developed for low-effort factor selection from these databases.

Closing the second gap (2) requires a method of analysis that allows for flexibly increasing the number of considered factors. A preselection of factors should be developed that require little preparation for evaluation and, therefore, are easy to incorporate into a location selection analysis.

Closing the third gap (3) requires streamlining the research, selection, and preparation of numerous factors to be considered. A thorough analysis of standard databases can significantly reduce the research workload.

Closing the fourth gap (4) requires accelerating less complex objective decisions. Factory planners need decision support to understand the effects that can be derived from the diverse planning information [14]. Decision support systems are methods and tools for data analysis, system modeling, and identification of optimal solutions [5]. Schuh et al. proposed a new data-based method for high-quality location selection decisions featuring a company-specific quantitative assessment of soft and hard factors. This method involves four key steps: industry analysis, regional determinants examination, location comparison through target functions, and sensitivity and scenario analysis of ranked alternatives. The method may be enhanced by dynamically analysing upcoming boom regions, enabling first-mover benefits. [1]

Closing the fifth gap (5) requires balancing a comprehensive approach to reduce uncertainty with a focus on the most critical factors. Due to today's uncertainties, the comprehensibility of location selection is especially important [2]. The level of detail or aggregation of the decision support determines the trade-off between low-effort usage and result accuracy [15]. Low-effort decision-making requires focus on the most essential aspects with minimal effort for information gathering [13].

Table 1. Summary of the gaps to close in factory location planning concerning digitalization

	State of the art	Demand	Closing the gap
First gap to close (1)	Predominance of quantitative factors	Consideration of qualitative factors	Guideline for factors selection
Second gap to close (2)	Low number of considered factors	High number of influencing factors	Expandable factor preselection
Third gap to close (3)	High difficulty for data research	Large scope of data research	Expandable data base preselection
Fourth gap to close (4)	High complexity of subjective decisions	Low complexity of objective decisions	Digital decision support
Fifth gap to close (5)	High uncertainty of subjective decisions	Low uncertainty of objective decisions	Comprehensibility and low-effort usage

4. Sustainability

The importance of sustainability as an influencing factor in manufacturing business decisions increases along with environmental policy pressure. This pressure originates from the public (government organizations, non-governmental organizations, customers) and the environment. Therefore, circular economy principles and the risks of climate change cannot be disregarded in the long run. This necessitates the consideration of sustainability in business activities with long-term implications, such as optimizing the supply chain and, consequently, the location selection for factories. [16,17] Besides, such considerations of ecological factors can result in economic and strategic benefits [18]. Without considering sustainability in location selection, the introduction of, e.g., European Sustainability Reporting Standards (ESRS) and legally mandatory sustainability targets for industrial sectors and locations will inevitably lead to costly factory modifications. Yet established approaches for location selection do not consider the various factors influencing sustainability, e.g., the possibilities for using and generating renewable energies.

Closing this gap requires the introduction of measurable and applicable Green Factory KPIs into the location selection process. This requires a methodological framework for translating Green Factory KPIs into location selection criteria [19]. Factors to be considered include, for example, the Green Factory KPI "CO_2 emissions of logistics". This Green Factory KPI can be incorporated into the location selection process by considering supply chain distances from a sustainability and economic perspective. The Green Factory KPI "Waste Recycling" can also be included in the location selection process by considering the proximity to suitable waste processing industries and the emissions generated during transportation. Furthermore, the choice of location influences not only Green Factory KPIs based on transport distances but also other factors, such as the proportion of internally generated renewable energy. This can be considered in the location selection process, for example, by taking the varying availability of solar-capable land into account.

5. Resulting Data Research Approach

In conclusion, the result regarding digitalization is the need for digital decision support systems. Such systems decrease the uncertainty, subjectivity, and complexity of location decisions. Uncertainty is reduced via analysis of extensive factors and data sets. Subjectivity is reduced by evaluating according to ranked individual objectives and unveiling development patterns invisible without algorithmic analysis. Complexity is reduced via digital automation of typical analysis steps. Therefore, this publication proposes a data research approach to identify suitable data for such decision support systems as a first step. One of the next steps in our future research will be the selection of databases to integrate into a decision support system.

The result regarding sustainability is the need for quantitative analyses of green factory KPIs to enable location selection according to sustainability objectives. The following steps are supposed to mitigate the non-consideration of sustainability in state-of-the-art location. First, we evaluate which Green Factory KPIs have the highest significant impact on overall sustainability performance of planned productions. Then, a cause-and-effect analysis will be carried out to examine how the choice of location influences the manifestation of these Green Factory KPIs. This cause-and-effect analysis can be conducted through a questionnaire-based empirical study involving experts in factory planning [20]. Taking into account the identified relevance of Green Factory KPIs on overall sustainability performance, the benefits of incorporating Green Factory KPIs in the location selection process must be assessed.

The data content is the first assessment dimension. The data must enable consideration of as many relevant location factors as possible. Only a fraction of the potential factors are suitable for any location selection case. The following ten main categories provide an overview of established assessment dimensions that each contain many location factors: market potential (C1), supply infrastructure (C2), freedom of trade (C3), labor market & workforce (C4), transfer payments & subsidies (C5), legal certainty (C6), political stability (C7), macroeconomic stability (C8), simplicity of business establishment (C9) and transportation infrastructure (C10). [1] A holistic selection of relevant factors and corresponding data sets is enabled by closing the described gaps regarding sustainability. We propose an extension of the ten categories by the following category: sustainability (C11). Thus, eleven categories of location factors are offered to assess the data content.

Data suitability is the second assessment dimension. In this dimension, the data can be assessed regarding the context fit of the contained information via three aspects: relevance (S1), trustworthiness of the source (S2), and trustworthiness of the included information (S3). In addition, the data can be assessed regarding the data structure quality via two aspects: comprehensiveness (S4) and granularity or level of detail (S5). In addition, the data can be assessed regarding the data value quality via two aspects: precision (S6) and currency, actuality, or timeliness (S7). In addition, the data can be assessed regarding its environment, including knowledge and governance, via one aspect: usability (S8). [21] Relevance (S1) in this context describes whether the content of data records meets the respective information needs. Trustworthiness of the source (S2) in this context describes whether the data source is perceived as reliable. Trustworthiness of the contained information (S3) in this context describes whether the data creation method is perceived as reliable, e.g., the data may be perceived as less reliable if it contains subjective interpretations recorded in surveys. Comprehensiveness (S4) in this context describes whether the data includes all entities in the desired scope about which information is required, e.g., if all states of the world are included. In this context, granularity or level of detail (S5) describes whether all entities contain the required information, e.g., if locations are broken down into countries, counties, or other classes. Precision (S6) in this context describes whether numerical values contain the desired number of places beyond the decimal point; e.g., they may not be considered precise if rounded. Currency actuality or timeliness (S7) in this context describes whether the data represents the required point in time. Usability (S8) in this context describes whether the data is findable and accessible.

The resulting data assessment method follows the described two dimensions (see Table 2). The aim is a holistic but practical assessment for identifying suitable data sets. Therefore, for each data suitability aspect, each blank would be filled with a brief description according to the influencing factors described above and a simple rating according to case-specific preferences. It is the basis for further research to identify suitable databases and analysis methods.

Table 2. Method for data assessment regarding content and suitability

		Data suitability							
		Context fit			Data structure quality		Data value quality		Governance
Data content		Relevance	Trust in source	Trust in information	Comprehen-siveness	Granularity	Precision	Currency	Usability
Main categories	Data set	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)
Market potential (C1)	Data set 1								
	Data set 2								
	Data set 3								
Supply infrastructure (C2)	Data set 4								
	Data set 5								
…	…								

6. Summary, conclusion and outlook

In summary, digitalization necessitates digital decision support systems to reduce uncertainty, subjectivity, and complexity in location decisions. Sustainability requires quantitative analysis of green factory KPIs to incorporate sustainability objectives in location selection. The proposed data assessment method follows the dimensions data content and data suitability, providing a practical approach to identifying appropriate data sets and databases for informed decision-making as well as further research and analyses.

In conclusion, such a targeted approach supports the further development of factory site selection processes. By incorporating two main future megatrends (sustainability and digitalization), the approach enables enterprises to realize strategical advantages. For example, factories strategically situated with a strong emphasis on ecological sustainability are likely to exhibit superior ecological performance, thereby facilitating adherence to regulatory frameworks and increasing long-term resource efficiency. This, in turn, translates into heightened resilience in the face of potential energy supply crises and shifts in legislation.

As an outlook, additional research leading to further publications is proposed. Next, the assessment method will be detailed to select location factors and suitable databases. Later, a prototypical software application will be presented. Its aim is the decision support in factory location selection based on analyzing the selected databases. Finally, the application will be evaluated. Further studies may be necessary to select data analysis methods and the desired form of results to be included in the decision support system.

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Biography

Dr.-Ing Michael Riesener (*1986) studied Industrial Engineering at RWTH Aachen University. Afterwards, he worked as a research assistant, group leader, and chief engineer at the Chair of Production Systems at the Laboratory for Machine Tools and Production Engineering, WZL of RWTH Aachen University. In 2015, he earned his Ph.D. in Innovation Management. He is also Managing Chief Engineer at the WZL, where he is particularly responsible for the Innovation Factory on the RWTH Aachen Campus.

Tobias Adlon, M.Sc. (*1989), studied industrial engineering at RWTH Aachen University, Germany, and Imperial College London, UK. After working in two management consultancies and the manufacturing industry, in 2015, he joined the Chair of Production Systems at the Laboratory for Machine Tools and Production Engineering, WZL of RWTH Aachen University, as a research associate. Since 2020. he has been Chief Engineer/ Head of the Factory Planning Department.

Esben Schukat (*1993) holds two degrees from RWTH Aachen University in the field of Mechanical Engineering and Economics and has been a research associate and group leader (assembly planning) at the Chair of Production Systems at the Laboratory for Machine Tools and Production Engineering, WZL of RWTH Aachen University, since 2019. Since 2023, he has been Chief Engineer/ Head of the Factory Planning Department while continuing his research activities on matrix-structured assembly systems.

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Carsten Engeln, M.Sc. (*1994) studied production engineering at RWTH Aachen University, Germany. Since 2022, he has worked as a research associate with the WZL of RWTH Aachen University. His Ph.D. project focuses on enabling factory optimization via automated creation of digital value stream transparency.

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