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Evaluating Changeable Production Logistics: A Multicriteria Approach

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ABSTRACT

In the current volatile business landscape, characterised by frequent disruptions and uncertainty, a future-proof production logistics system is essential for ensuring efficient and effective operations. The unpredictable changes in production logistics pose significant challenges which cannot be met by flexible solutions with limited solution corridors. In response, the concept of changeability emerges as a solution offering resilience and transformability in the face of uncertainty. Given the dynamic nature of the business environment, there is a need to shift focus from solely economic viability to considering broader factors such as changeability, sustainability, and social impacts. Evaluating and selecting appropriate changeability strategies for production logistics remains challenging in practice and academia. This paper addresses this challenge by proposing a multicriteria approach that integrates economic, environmental, and social dimensions into evaluating changeability options. This approach emphasises the balancing of production logistics objectives, such as high performance, quality, and low costs, with sustainability and social responsibility considerations. Furthermore it reassures the reader about the feasibility of managing dynamic influences in the business landscape. Ultimately, this research contributes to enhancing the understanding of changeability as a strategic imperative in modern production environments and offers practical insights for effectively managing dynamic influences in the business landscape.

Keywords: Changeability, Multicriteria evaluation, Production logistics, Transformability, Industry 5.0

INTRODUCTION AND RELEVANCE

In the ever-evolving production landscape characterised by various disruptions and uncertainties, the role of production logistics in ensuring operational efficiency is paramount. The increasing challenge is that production, and with it, the supplying production logistics must adapt to dynamic and unpredictable changes due to climate change, pandemics and other global conflicts.

In the practice of many manufacturing companies, external consulting firms plan production logistics (Klug, 2018). They develop various planning alternatives, which are then evaluated by the company's internal teams based on multiple criteria. However, cost factors usually override the evaluation and changeability is not sufficiently considered (Schulte, 2017). The traditional focus solely on economic viability is no longer sufficient. A paradigm shift towards considering resilience, sustainability, and social aspects is imperative. These considerations are the cornerstones of Industry 5.0 (Huang et al., 2021; Vogel-Heuser and Bengler, 2023) which can be achieved through changeability.

By emphasising the concept of changeability - the ability to undergo significant structural changes in response to unpredictable internal and external influences (VDI 5201) - this research contributes to a deeper understanding of the strategic imperatives in modern production logistics environments. It highlights the importance of embracing change and fostering resilience while addressing economic, sustainability and social concerns.

This paper addresses the challenge of evaluating and selecting appropriate strategies to enhance changeability in production logistics while considering these multifaceted dimensions.

While product changes and their effects have already been widely studied in research on a factory level, production logistic-side change management is still in its infancy (Drabow and Woelk, 2004; Hawer, 2020; Kaucher et al., 2021; Erlach et al., 2022). Although production logistics is a critical component in the value chain of manufacturing companies, little research deals specifically with the assessment and evaluation criteria of the changeability of production logistics. Closing this gap in the literature is the focus of this publication, and it opens up the possibility of gaining new insights in this area.

This publication aims to develop a method for evaluating planning alternatives in production logistics that does not focus exclusively on economic indicators but, above all, considers the changeability of the system. In addition, further evaluation criteria, such as sustainability and social aspects, are included to enable the most comprehensive possible evaluation of the given alternatives.

FUNDAMENTALS

Changeability in Production Logistics

In the uncertain and constantly changing environment of the 21st century, it is becoming increasingly difficult to reliably assess future developments, so flexibility in limited solution corridors alone is not enough to survive in today's global competition (Drabow and Woelk, 2004; Dürrschmidt, 2001). This problem can be solved by changeability. It enables an appropriate and forward-looking (re-)action to unforeseeable events (Zäh et al., 2004). To be changeable, a suitable combination of flexibility and responsiveness is necessary (Reinhart et al., 2002; Cisek et al., 2002). Responsiveness is described as the ability of a system to adapt quickly and with little effort to unforeseeable situations (Drabow and Woelk, 2004). On the other hand, flexibility is determined as a passive ability to change to known influences and with restrictive scopes of action. Westkämper et al. distinguish between versatility and changeability. While versatility only considers technical aspects, changeability also includes social subsystems (Westkämper and Zahn, 2009; Heinecker, 2006).

Hernández distinguishes between technical, spatial and organisational changeability. Technical changeability encompasses all technical systems and their ability to be reconfigured. Spatial changeability covers the ability to expand and reduce the space, while the organisational dimension refers to the ability to change the organisational structure and its processes.

A system is described as capable of change "if it has process, structural and behavioural variability that can be used in a targeted manner. Systems capable of change can make anticipatory interventions in addition to reactive adjustments. These activities can respond to changes in the system as well as to changes in the environment" (Westkämper and Zahn, 2009).

The change potentials are designed to be implemented if necessary and only trigger costs and time expenditure during implementation (Cisek et al., 2002; Nyhuis et al., 2008). Changeable systems are, therefore, solution-neutral and do not specify a particular direction of change, whereby the framework of possible changes is preconceived (Cisek et al., 2002; Zäh et al., 2004).

Change enablers can be characterised as a property or function that supports the ability of a system or organisation to transform and cope with change (Hernández Morales, 2002). The literature usually refers to the five primary enablers of change: universality, mobility, scalability, modularity and compatibility (Wiendahl et al., 2024; Hernández Morales, 2002). These five primary enablers can be subdivided to enable differentiation and detailing (Hawer, 2020; Pachow-Frauenhofer, 2012; Vollmuth et al., 2024).

Increasing the changeability of existing systems is often associated with investment costs (Hernández Morales, 2002). The aim is to enable a fast and cost-effective conversion process and minimise possible additional investments. The aim is to find the best possible balance between the necessary change capability and the lowest possible system life cycle costs.

Multicriteria Decision Making

For evaluating planning alternatives in production logistics, a structured approach and considering various criteria from different areas, such as economic efficiency, sustainability, social aspects or changeability, are essential. The various evaluation criteria partly depend on or contradict each other, resulting in a conflict of objectives.

Evaluating alternatives to solve problems with multiple objectives requires multi-attribute decision-making methods (MADM). A change that leads to an improved achievement of one objective can make it more difficult to achieve another. In addition, objectives may have different units and are, therefore, difficult to compare. Some objectives can be evaluated quantitatively, others qualitatively (Zimmermann and Gutsche, 1991). MADM can be divided into various sub-categories. One category is the utility based techniques with examples like Analytic Hierarchy Process (AHP) or the utility analysis (Danesch et al., 2018).

The AHP, according to Saaty, is a method for evaluating alternatives, representing the ranking of these alternatives (Saaty, 1977). Analytic means that the decision problem is broken down into smaller, independent sub-problems (single objective decision-making problems) to analyse them separately. The results are then summarised to identify the best possible solution for the overall problem. Pairwise comparisons enable the inclusion of both tangible and intangible evaluation criteria. The AHP utilises a hierarchical structure in which the individual elements are linked linearly (Saaty, 1990; Saaty, 1977; Gärtner et al., 2024).

METHOD FOR EVALUATING PRODUCTION LOGISTICS

The procedure of the evaluation method is shown schematically in Figure 1. This section provides an overview of the method. The individual steps are described in more detail in the following chapter.

Scenario management is applied as a first step to determine the most critical drivers of change and the areas of production logistics in which changeability is essential. Next, based on the identified change scenarios and overarching corporate goals, the specific objectives of production logistics are derived. Evaluation criteria can be deducted from the identified objectives, which are then used to evaluate the various alternatives. To determine the performance of the options available for selection concerning the evaluation criteria, it can be helpful to simulate production and the production logistics alternatives. The multi-criteria evaluation is then carried out according to the AHP, which was identified as suitable for multi-criteria decision methods. As companies must first and foremost be economically viable to be successful in the long term, a profitability test of the alternatives is then carried out to demonstrate that the selected alternative is financially viable. During the entire process, care must be taken to ensure that the results and justifications are documented wholly and comprehensibly to make the decision-making process understandable and

transparent and to be able to justify decisions in the event of subsequent queries (Fottner et al., 2022).

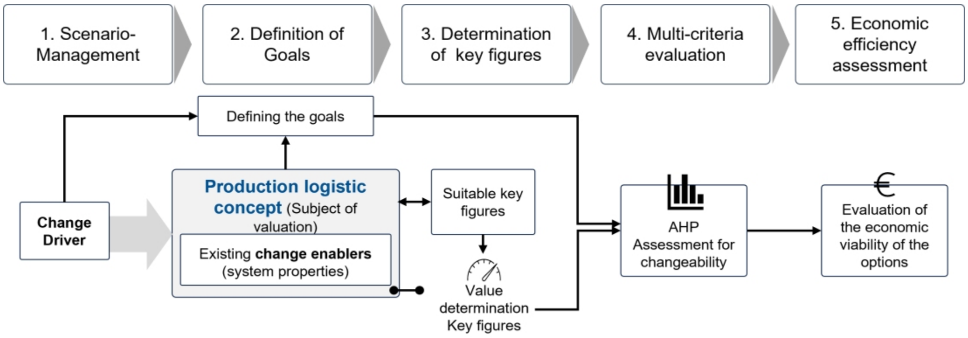

Figure 1: Schematic process of evaluating planning scenarios in production logistics.

Scenario Management

To determine a sensible dimensioning of changeability, it is necessary to systematically consider and estimate future developments with the help of futurology methods—considering various possible futures and trends results in future-proof and resilient production logistics (Kaucher et al., 2021). Kaucher et al. investigate the suitability of different approaches to support the planning of factories that can better cope with future challenges. They showed that the scenario technique, particularly scenario management according to Gausemeier et al., is suitable for this purpose (Kaucher et al., 2021; Gausemeier et al., 1998).

In the first step, the production logistic system is considered in its current state and factors that influence future development are determined (Gausemeier et al., 1998). From these influences, the relevant key factors are defined with the help of a relevance analysis based on pairwise comparison (Gausemeier et al., 2017).

In the subsequent step, up to three possible future developments are worked out for each key factor, based on which different scenarios are created. Based on the results, meaningful goals for future production logistics can be determined (Gausemeier et al., 2017, 1998).

Identification of Goals

Formulating specific goals is an essential step in planning a successful company and its production logistics (Lindemann, 2009). Goals specifically for production logistics can be derived from the organisation's overarching goals.

The overarching goals in logistics traditionally include increasing logistics performance and reducing logistics costs. These can be expanded to include the dimensions of lean logistics, sustainability, social issues and changeability. A comprehensive presentation of possible goals of production logistics can be found in Figure 2.

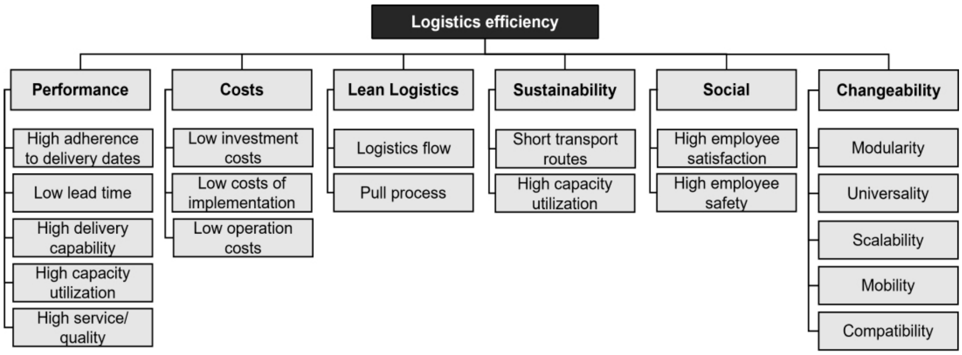

Figure 2: Logistics goals.

In this work, the *performance-related* goals are divided into the sub-goals of high adherence to delivery dates, short lead times, high delivery capability, high capacity utilisation and high service and quality.

As described, the *logistic costs* are subdivided into investment, implementation and operation costs. The traditional goals of performance and costs are to be supplemented by further relevant areas.

Lean processes are based on the value stream and are characterised by their effectiveness, efficiency and waste avoidance. The extent to which lean logistics objectives are achieved can be determined, for example, by the logistical flow or the implementation of the pull principle (Dörnhöfer, 2017).

Environmental and ecological goals are also important, as they are increasingly demanded by the public (Hohmann, 2022). Traditional logistical processes negatively affect the environment due to energy consumption, space requirements, emissions of pollutants and waste generation (Arnold et al., 2008). Regarding production logistics, ecological goals relate to efficient resource use and reduced emissions, which can be measured using the CO_2 equivalent. A sustainable flow of goods results from short transport routes and high plant capacity utilisation (Hohmann, 2022). Furthermore, changeability can enhance the life span of production logistic systems through well-planned solution neutrality of the systems and retrofit options and thus reduce the environmental impact (Wünnenberg et al., 2022).

The *human factor* is a critical success factor for companies and their ability to change. The success of integrating new technologies and processes is highly dependent on employee acceptance. For this reason, the involvement of employees is essential for the ability of a company and its production logistics to react quickly (Fottner et al., 2022). A company's and its employees' willingness to change is essential for a successful change process. Not only the acceptance but also the active participation of employees supports change. Due to the importance of employees for a company, employee safety and satisfaction are among the social goals of a company.

In addition, there is also the *ability to change* due to the increasing demands and the turbulent environment of companies. The changeability of a system can be characterised using the five change enablers described in the previous section.

Key Figures

Various evaluation criteria and their key figures can be identified to check whether the set goals have been achieved. The evaluation criteria can be derived from the goals and requirements of a system. They are used to evaluate alternative options for action in the field of change, as they offer the possibility of simplifying and comparing complex processes and structures.

Nyhuis and Wiendahl point out that a subdivision of production logistics makes sense due to its complexity and diversity (Nyhuis and Wiendahl, 2012). The evaluation criteria are structured along three dimensions, as shown in Figure 3. As the evaluation criteria can be derived from the goals of production logistics, these goals form one dimension. From the process point of view, the production logistics can also be subdivided into the subsystems of transportation, handling and storage (Hohmann, 2022). Furthermore, the system can be viewed from the resources dimension and subdivided into organisation, space, technology and staff categories (Heger, 2007). The selection of evaluation criteria directly influences the evaluation and selection of planning variants. By prioritising or neglecting specific criteria, the orientation of the decision-making process is precisely controlled. More than 110 possible evaluation criteria from the literature and practice were collected. The criteria were assigned to the dimensions of goals, processes and resources, as seen in the example of the warehouse occupancy rate in Figure 3.

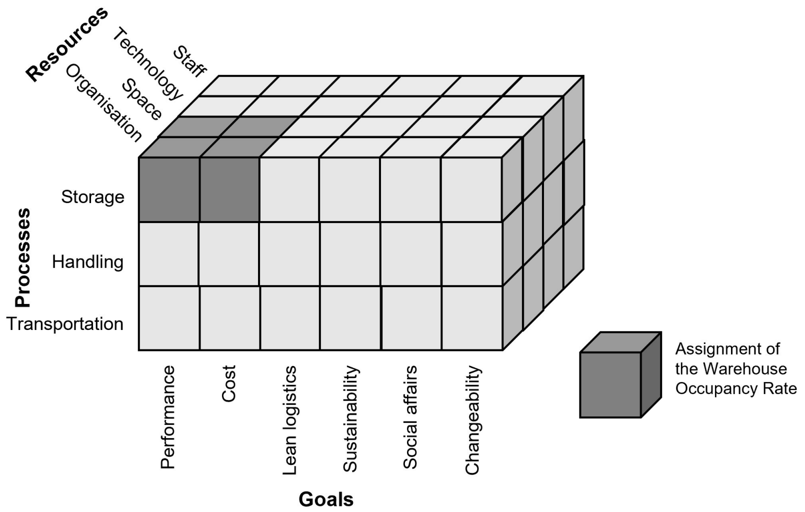

Figure 3: Classification of the evaluation criteria according to the three dimensions; exemplary categorisation of the warehouse occupancy rate.

Multicriteria Decision Making

The aim of evaluating planning alternatives in production logistics is to determine the best possible alternative. Many goals and criteria must be considered, and an evaluation is only possible through a combination of several quantitative and qualitative key figures, some of which conflict with each other (Dürrschmidt, 2001). Multi-criteria evaluation methods offer the possibility of evaluating different alternatives based on several criteria.

The decision hierarchy is structured for this purpose, as illustrated in Figure 4. The first level is the overarching objective, which can be subdivided into goals. The level of the evaluation criteria follows this. The different alternatives form the lowest level.

The AHP is carried out using a simplified example in which three planning alternatives (A-C) are to be compared based on the selected goals of performance and changeability, each with two evaluation criteria.

Subsequently the evaluation of the alternatives is caried out using AHP. In the first step, the weightings of the performance and changeability goals are determined by pairwise comparisons and presented in a matrix. The local priority is then determined by determining the eigenvector and normalizing it to 1. The same methodology is applied to both the evaluation criteria (step two) and the alternatives (step three), whereby the alternatives are evaluated separately for each evaluation criterion. A consistency check is carried out for each matrix to ensure the logical consistency of the pairwise comparisons and evaluations. Finally, the global priorities of the alternatives are determined in step four, which shows which alternative is the preferred alternative, taking into account the selected evaluation criteria.

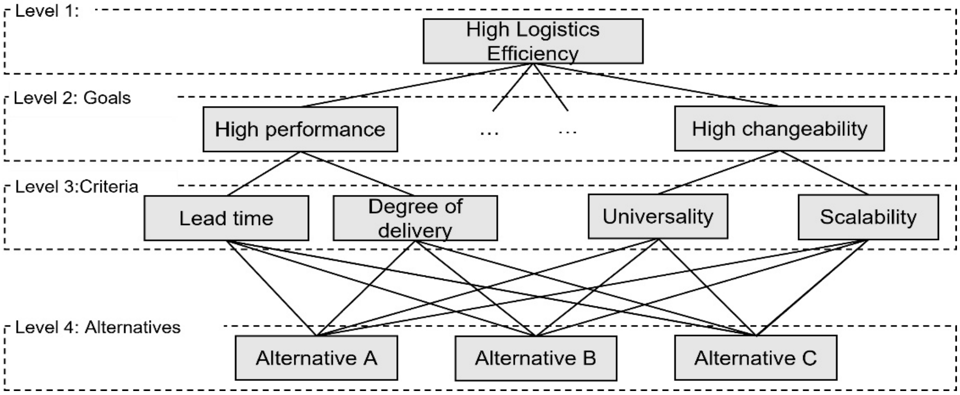

Figure 4: AHP hierarchy.

Profitability Calculation

When evaluating logistics systems, financial objectives are often the main focus due to their importance for the existence of the company (Grinninger, 2013; Baur and Blasius, 2022). Economic efficiency is also evaluated since the development or change of production logistics is associated with investments and capital commitment. Investment appraisal methods compare and evaluate the economic efficiency of different planning alternatives (Fottner et al., 2022). Since changeable systems can represent a higher investment than inert systems at the time of purchase but save costs in the long term, it is essential to consider a system life cycle. The net present value method shows the financial success of an investment by discounting the cash inflows and outflows to a specific point in time. However, only actual costs are considered, not imputed costs such as depreciation. The net present value can be calculated using Formula (1) (Fottner et al., 2022):

$$NPV_0 = -I_0 + \sum_{t=0}^{T} \frac{CF_t}{(1-i)^t} \tag{1}$$

The discounted payment surpluses (Cashflow (CF_t) as the difference between incoming payments and outgoing payments, discounted with discount rate i) of the period under consideration T, are added to the initial investment (I_0). A positive net present value indicates the profitability of an investment.

When applying the method, it is essential to consider the forecast scenarios and the associated change and conversion costs. Formula (2) calculates the minimum total costs (TC) of change over a system's life cycle (Zwißler and Gebhardt, 2013).

$$min\{E\left(TC_{gk}\right) = CCO + \sum_{i=1}^{I} h_{i,\ normalized} \sum_{x=1}^{X} \sum_{j=1}^{J} p_{xj} \cdot CPC_{xj}\} \qquad (2)$$

The total costs include the conversion process costs (CPC) and conversion object costs (CCO), accumulated over the object's or system's useful life. The probability of occurrence for the conversion frequency ($h_{i,\ normalized}$) depends on the future scenarios (j) and their likelihood of occurrence (p_{xj}). The aim is to identify the optimal combination of change enablers to keep costs as low as possible (Zwißler and Gebhardt, 2013).

DISCUSSION AND FURTHER RESERACH

This work aimed to develop a procedure for evaluating planning alternatives in production logistics and to enable the evaluation of changeable production logistics. The developed method comprises a total of six steps.

A procedure has been developed that enables a comprehensive evaluation of alternatives to be carried out and offers the possibility of considering different planning objectives. Not only is the changeability of a system considered differentiated, but other goals such as profitability or sustainability and social aspects are also included. A company's production logistics is a pervasive system, so it can be challenging to evaluate the entire system. For this reason, the evaluation criteria are broken down into transport, handling and storage processes.

The evaluation of changeable production logistics also continues to pose a challenge. As both too much and too little changeability are associated with increased costs for a company, estimating the optimum level of changeability required is essential. This is based on the forecast of future developments and is therefore associated with significant uncertainties. Consequently, assessing the necessary changeability of production logistics is a particular challenge. In addition, changeability is a system characteristic that is difficult to grasp and measure. Based on existing approaches, this study proposes to evaluate changeability based on the changeability enablers. Future research efforts are required to improve the measurability of changeability further.

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