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Towards A Holistic Cost Estimate Of Factory Planning Projects

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Abstract

As an interdisciplinary and complex task, factory planning lays the foundation for the economic efficiency of factories. Factory planning projects significantly influence the financial situation of production companies due to their high capital requirements and long lifetime. Today's inaccurate basis for decision-making in cost estimation leads to serious financial challenges in the future. Costs must be estimated with sufficient reliability to avoid misinvestments. There is currently a need for research for a holistic and systematic approach. This is partly due to the many requirements such an approach must meet. In this context, the paper aims to determine the requirements for a holistic approach to cost estimation in the early phase of factory planning projects. Based on a literature review, four key requirements for a holistic cost estimate could be identified and prepared for an approach. This includes the joint consideration of the interactions between spatial and process requirements. In addition, the early planning phase is challenging, in which little reliable information is available, but costs can still be sufficiently influenced. Furthermore, the operating costs during factory operation must be considered over and above the specific investment. With the help of various factors influencing factory design, scenarios should be generated and compared early to counter future opportunities and risks in the best possible way. These requirements can now be used for an approach to be developed that enables holistic cost estimates in the early phase of factory planning projects.

Keywords

Factory planning; Cost estimate; Early planning phase; Life cycle costs; Capital expenditures; Operating costs; Scenario design; Total Cost of Ownership

1. Introduction

Factory planning is crucial for the subsequent economic success of companies [1]. This is mainly because decisions within factory planning are often of strategic and long-term consequence [1,2]. Due to the highly dynamic business environment, ever shorter product life cycles and increasing customer requirements, the challenges for manufacturing companies are constantly increasing [3]. This also increases the challenges for factory planning. The realisation of factory planning projects, especially large-scale development and expansion planning projects, significantly impacts companies' liquidity due to the high capital requirements [1,4]. On the one hand, this is due to the considerable investments in production and process technology (process view) as well as in construction and building equipment (spatial view) [5]. On the other hand, operating costs, such as personnel and energy costs, influence the total costs and profitability of factories and their elements [2,6,7]. Due to the long life cycle of factories [8], the highest costs occur in terms of operating costs in the factory operation phase, despite high initial investments [9–11]. However, often only investments are used as a basis for decisions regarding project realisation, which can lead to erroneous cost estimates and misinvestments [12,13]. In this context, incorrect cost estimates and the associated wrong decisions can lead small and medium-sized enterprises (SMEs), in particular, into serious financial difficulties. This is also because SMEs lack the resources and necessary know-how, especially for investment controlling [14]. In Germany alone, with over 3000 building permits for factory and workshop buildings

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[15], approximately 130 billion euros were invested in new buildings and equipment in terms of machinery and devices in 2021 [16]. However, statistical evaluations show that cost targets are missed in factory planning projects in more than 70% of the cases [17]. For large infrastructure projects, studies indicate that even an average cost overrun of 37% can be expected [18]. At this point, it is essential to note that these studies are limited only to investments, usually from the construction point of view. The operating phase, which leads to a much higher share of costs due to operating costs, has not yet been considered here. Overall, incorrect decision-making principles in cost planning for the construction and operation of factories today lead to serious financial challenges in the future.

The points mentioned underline the relevance of an early, holistic cost estimate for planning projects. Therefore, this paper aims to review the current state of the art in this context, derive current research needs, and review relevant topics for and requirements of cost estimation to prepare for a holistic approach.

2. State of the art and need for research

Several sources underline the problem of finding an appropriate and practically applicable solution for cost estimates [19–22]. In practice, estimates are often based only on expert opinions and are therefore subjective and not reproducible [23,24]. The following, therefore, identifies the requirements necessary for a holistic and reproducible cost estimate. First of all, the relationship between process and building planning is often neglected [2]. This must be avoided since the central building requirements must be derived from the technical process [2,25]. As an interdisciplinary and complex task, factory planning and the associated cost estimation must consider the planning of production and logistics processes (process view) and other disciplines, such as building equipment and architectural planning (spatial view) (requirement 1). Furthermore, the foundation for a factory planning project's economic efficiency and functionality is already laid in the early planning phase [1,4]. The most significant share of the investment is determined at an early planning stage, so the most significant influence on costs can still be exerted there [8]. This approach comes, among other things, from product planning, where a large part of the costs is already determined at the beginning of product development [26]. This knowledge must also be transferred to cost estimation in factory planning (requirement 2). In previous work, the existing literature and approaches regarding cost estimation from an investment perspective (CAPEX) in the early planning phase have been discussed in detail [27,28]. However, life cycle costs comprise investments and operating costs [29]. Therefore, in addition to the investment view, operating costs (OPEX) must also be considered for a holistic cost estimation [6,28] (requirement 3). Each factory is unique and requires case-specific solutions [2,30]. Cost estimates are always subject to uncertainties [31]. The so-called scenario concept allows for opening up a space of possible futures and thinking through possible decisions' effects [32]. Transferring scenario management as an established strategy planning method to factory planning has proven very useful [33]. To obtain a valid basis for decision-making with a longer-term view of opportunities and risks within a cost estimate, it is therefore appropriate to compare different planning scenarios regarding content and related costs (requirement 4). In addition to the four derived requirements, a holistic cost estimate must meet general basic requirements. These include, among others, a high level of standardisation concerning existing approaches and a high degree of application focus for practical use.

Conducting a literature review provides the foundation for research work [34]. A systematic search procedure was conducted to identify relevant sources and existing approaches to holistic cost estimation. The search process focused on works that can be assigned to the context of the keywords factory planning, cost estimation, life cycle costs, total cost of ownership and early planning phase, and their links. Figure 1 shows the results of an intensive literature review of existing approaches and their analysis concerning the derived requirements (R1-R4). The basic literature [1,2,4,8,35] focuses predominantly on planning procedures and does not include holistic approaches to the associated cost estimation. According to WIENDAHL [2], the approaches analysed are subdivided according to the levels of detail in the factory. These can be assigned to the factory fields of technology, organisation and space and subdivided into the hierarchy levels of factory, section and workstation. The factory can only be considered and evaluated holistically if all levels up to the level factory are considered [2].

R4: *Consideration of different scenarios*
R3: *Consideration of CAPEX and OPEX*
R2: *Application in the early phase of planning*
R1: *Consideration of process and building*

	Source	building	process	early phase	CAPEX	OPEX	scenario design
factory	Brieke (2009)	◑	◑	○	●	◑	○
	Cevirgen et al. (2021)	●	○	●	●	○	◑
	Götze et al. (2013)	○	●	○	◑	◑	◑
	Heinemann et al. (2013)	◑	●	◑	◑	◑	○
	Hingst et al. (2023)	◑	●	○	◑	●	○
	Kovacic et al. (2016)	●	○	◑	●	●	◑
	Möller (2008)	◑	●	○	◑	◑	◑
	Nielsen et al. (2016)	◑	●	○	◑	◑	○
	Rieke et al. (2023)	●	◑	●	●	○	◑
section	Aurich et al. (2009)	○	●	○	●	●	○
	Dreier, Wehking (2016)	○	●	○	◑	●	○
	Heinemann et al. (2014)	◑	●	◑	●	●	◑
	Pohl (2014)	◑	●	○	●	◑	◑
station	Dehli (2020)	○	●	○	●	●	○
	Denkena et al. (2010)	○	●	○	●	●	◑
	Herrmann et al. (2011)	○	●	○	●	●	○
	Kampker et al. (2013)	○	●	◑	●	●	◑
	Lindner, Götze (2011)	○	●	○	●	●	○
	Mattes et al. (2012)	○	●	○	●	●	○
	Osten-Sacken (1999)	○	●	○	●	●	○

legend: ● focus ◑ partly covered ○ not covered

Figure 1: Analysis of existing approaches concerning the derived requirements [9,27,28,36–51]

Research and analysis of the literature show that single requirements are partially fulfilled, whereby approaches to the cost consideration exist due to the comparably simple object of consideration, in particular on the level of the workstation. At the factory level, approaches only take into account partial areas and do not consider interrelationships, such as between the spatial and process view or the investments and operating costs. Furthermore, only a few approaches consider different scenarios to generate planning alternatives and compare them with each other. Beyond the approaches considered, there are standards and guidelines [29,52–54] that only contemplate sub-areas from the building and factory planning and the cost view separately. The different approaches often concentrate only on small focus areas without considering holistic relationships and interactions. In summary, it can be said that with current approaches, methods and tools, a holistic cost estimation based on the derived requirements is not or only insufficiently possible. Own preliminary work in cost estimation, feasibility studies, life cycle considerations [27,28,36,37], and numerous consulting projects in companies underline the mentioned need for research.

The introduction of the problem definition, the consideration of existing approaches, and their discussion underline the research need for a holistic approach to the cost estimate of factory planning projects. In the following, the derived requirements and main focuses will be analysed, detailed and prepared as a basis for a holistic approach.

3. Requirements for a holistic approach to cost estimation

According to WIENDAHL [2], the principle of completeness before accuracy applies to cost estimation. A holistic cost estimate is required in the early phase to achieve this completeness. Figure 2 summarises the requirements for a holistic approach to cost estimation derived from past planning projects and the literature (Compare derivation of requirements and literature review in Chapter 2). *Capital expenditures* and *operating costs* must be considered jointly. These are determined in the factory primarily by the planning and designing of the *spatial and process view* and combined form the *life cycle costs*. Since one of the purposes of cost estimates is to minimise risk for companies, an estimate must be feasible at an *early planning stage*. The uncertainties associated with an early planning phase must be reduced as far as possible using a systematic procedure. In this context, every factory is unique [6]. Nevertheless, it is possible to identify general *factors that fundamentally influence* factory design and configurations. The specification of the influencing factors directly impacts the costs and leads to different *factory scenarios* depending on the configuration.

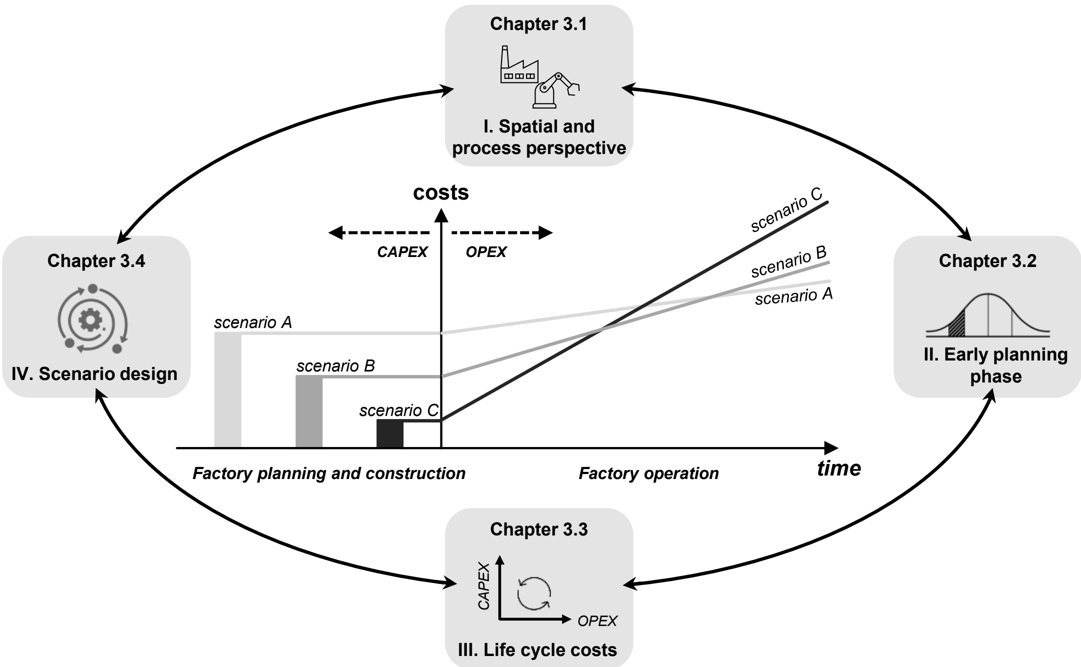

Figure 2: Overview of requirements for a holistic approach to cost estimation, own figure

Different scenarios during the planning and construction of investments lead to different specifications in the operating costs over the life cycle (example shown in Figure 2). In the following, the individual requirements will be scientifically specified and analysed to make them applicable to a holistic approach to cost estimation.

3.1 Synergetic cost estimate from spatial and process view

In order to systematise the interdisciplinary and complex planning tasks in the factory planning process, the planning procedure has been described by various authors [1,2,4,8] and summarised in the renowned guideline VDI 5200 [55]. Traditionally, in factory planning, the sequential planning phases are run through in a linear sequence, and the level of detail increases successively with advancing phases [2,55]. The interdisciplinary approach of synergetic factory planning has significantly contributed to VDI 5200 (Figure 3) [2]. This approach addresses the interdisciplinary character of factory planning. It combines the spatial view, i.e. the interior and exterior design of factories from the perspective of architectural and construction planning [56], with the process view, i.e. the design of the technological and logistical processes and the operating resources [2]. To develop a sustainable and successful factory concept, the requirements and the interactions from the process and spatial perspectives must be considered synergetically [2].

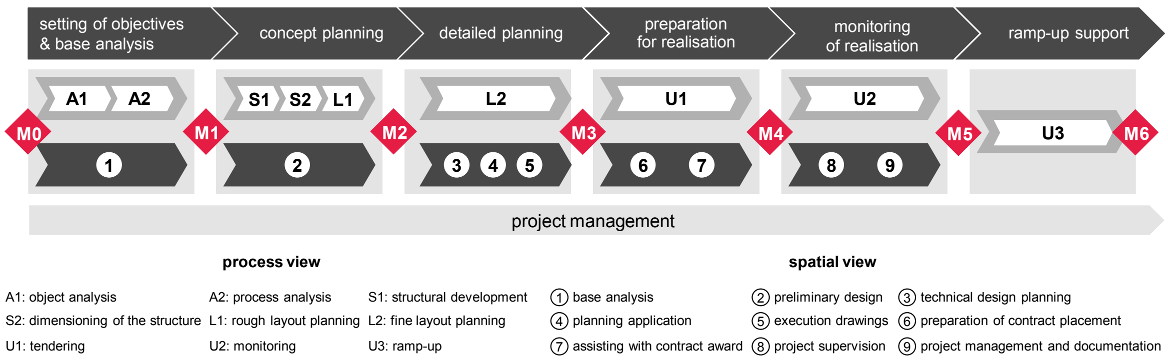

Figure 3: A process model of synergetic planning from a spatial and process perspective, adapted from [2]

Only by synchronising the building with the process is it possible to respond adequately to the rapid changes in the product and the technical equipment [57]. Future challenges require an even stronger focus on the interdisciplinary character of factory planning [58]. To reduce planning time and errors, process-side requirements (including equipment weights, equipment foundations, vibration sensitive areas) can be coordinated with the spatial specifications in a cooperative, efficient and early coordination process [2]. Increasing requirements from the process point of view also leads to increased costs in the building and the technical building equipment (e.g. through higher m² or m³ prices). Depending on the requirements, areas can be categorised, for example, into low, medium and high requirements with specific parameters. Depending on the category, different area parameters and building types lead to different cost characteristics based on comparative values (e.g. with the help of BKI [59]). Experience from past planning projects shows that inadequately combined consideration of costs leads to increased follow-up costs (e.g. reinforcements of the base plate, retrofits in the supporting structure and technical building equipment). For this reason, the synergy from a spatial and process view, e.g. following the process model of synergetic factory planning, must be considered in a holistic approach to cost estimation.

3.2 Consideration of the early planning phase

The foundations for the functionality and profitability of any factory planning project are set in the early phase [1,4]. Most investments are determined at an early planning stage, which is why the most significant influence on future project costs can also be exerted there [8]. The factory planner is faced with significant challenges in this process. On the one hand, the project scope and the associated costs are determined in the early phase [1,4]. On the other hand, the early phase is characterised by uncertainty, so information and data are often unreliable [23]. Costs are determined in an early planning stage but only occur in subsequent planning phases in which they can no longer be sufficiently influenced [60–62]. Figure 4 shows this dilemma and the determination of the early phase for the holistic approach to be developed.

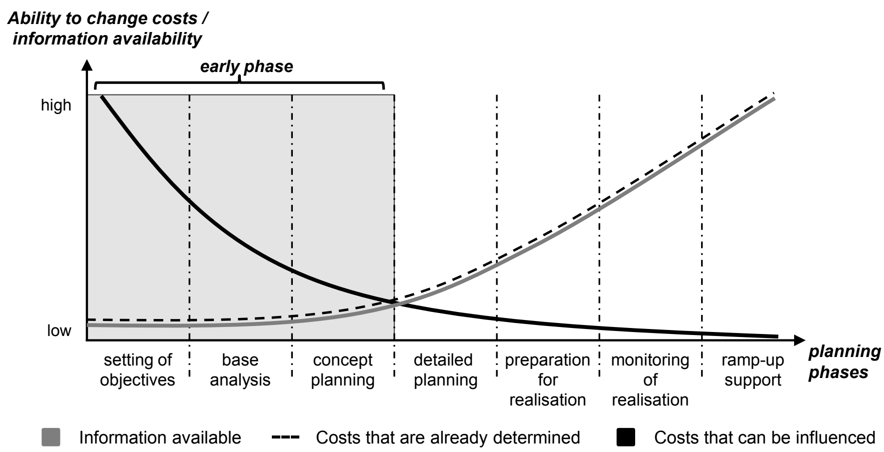

Figure 4: Cost occurrence and cost influence in the early planning phase, own figure adapted from [60–62]

As shown in Figure 4, in this paper, the early planning phase of factory planning is defined up to and including concept planning, in which the cost influence is still high. As the planning period and level of detail advance, the cost influence decreases, and costs can only be influenced and determined within the framework of the concept that has already been developed [2,55]. In practice, another aspect becomes relevant. Frequently, projects cannot even be released and started without a cost or budget estimate. The reasons presented, already underlined by own preliminary work [28,63], emphasise the necessity of a decision-making tool in the early planning phase.

3.3 Consideration of the life cycle costs of factories

In the basic literature, the stages of the factory planning process are seen as an investment process [1]. Capital expenditure is generally understood as the use of capital and, thus, the long-term commitment of financial resources to assets [64–66]. In addition to the often exclusive consideration of investments as decision support, so-called operating costs are incurred in the factory during the operating phase, often exceeding the investments after only a few years [2,67,68]. Due to the time component, investments and operating costs have a different impact on companies' value generation and cash flow. Thus, input data of the investment calculation are often associated with uncertainties and risks that must be included in the calculation [64,69]. In the case of real estate, capital expenditure accounts for only 20% of the life cycle costs, while operating costs account for 80% [70,71]. Even for machine tools, operating costs can cause 80% of the life cycle costs [13]. The remedy for decision support is the consideration of the life cycle of objects and their associated costs. The life cycle describes generally typical patterns of a system over time [12]. Life cycle costing (LCC) methods holistically consider life cycle costs over the life of objects and thus support the purchase of capital-intensive and capital goods with long lifetimes [72,73]. Despite different terms for life cycle costs, all definitions share that costs are summed up over the life cycle to show the trade-off between initial and follow-up costs [74]. The long lifetime and high investments underline the necessity of a life cycle consideration of factories [37,75]. The life cycle of the factory and its elements can be divided into higher-level phases of factory planning and construction, factory operation and factory reconfiguration and end of life [76]. The factory life cycle can be divided into different life cycles, such as the product, component or process life cycle [2,77]. The life cycle of a factory usually extends over 30 to 50 years, whereby the individual elements of the factory, such as machines, have a shorter life cycle [8,78]. Figure 5 shows the exemplary life cycle and the associated costs of the factory and its elements.

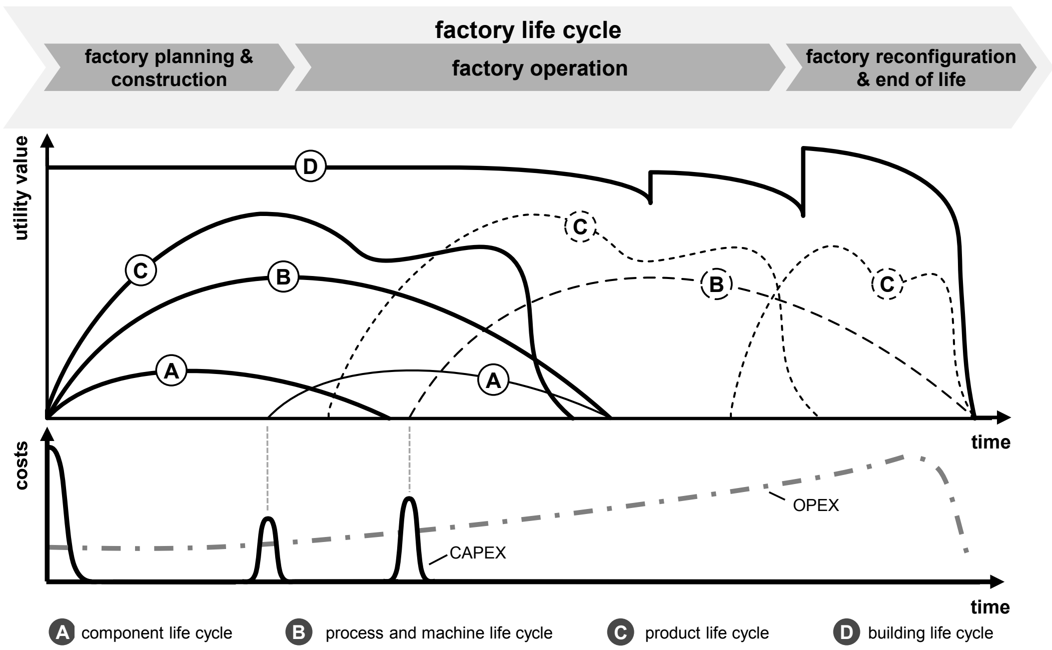

Figure 5: Exemplary life cycle and costs of factories and their elements, own figure adapted from [36,76,79]

The figure also outlines the costs underlying the life cycle as an example. These are represented by the two exemplary CAPEX peaks in Figure 5. After high initial investments, further follow-up investments become necessary depending on the lifetime of the components and machines. The investments are displayed simplified and independently of possible payment flows as fixed-step costs. The operating costs rise constantly in this case due to, for example, increasing energy, personnel or maintenance costs. Figure 5 underlines the relevance of the operating costs in the production life cycle costs due to the long lifetime. This also highlights the fact that the factory planning phase has a critical influence on life cycle costs [1,4]. Factory operation, with a duration of several decades, is the longest and, thus, the most crucial phase in the life cycle of factories [9,10]. This emphasises the trade-off between CAPEX and OPEX, which must be considered holistically in spatial and process view interaction. The objective of companies is to enable the production of a maximum outcome with the lowest possible operating costs [80]. However, the determining factors for this are already set in the planning stage, which is why an early lifecycle-oriented cost estimate is essential.

3.4 Consideration of influencing factors for scenario design

Each factory planning project is unique due to the different processes and products [2,35]. In addition to established procedural steps for factory planning, it is possible to identify generally applicable influencing factors on factory design. In this context, design or structure-relevant influencing factors are those factors that have a structural impact on the subsequent factory design and layout. Influencing factors can be divided into external and internal influences [2,80]. External influencing factors, such as increases in the price of materials or energy [81], can only be considered to a limited extent, so although they influence costs, they can only be insufficiently influenced by factory planning. Internal influencing factors are factors that directly impact the factory design. For example, these influencing factors can be derived from different factory types in the literature [35]. Examples are the degree of automation, product specifications (size, weight) or the number of variants [8,35]. At this point, the fuzzy logic method is an option for modelling the uncertainty [82], which is present due to the early planning phase. The subsequent impact of these influencing factors is often already determined in the early planning phase. It has a direct influence on the design of the factory and its life cycle costs. With the methodical aid of the factory objects as elements of the factory [83], Figure 6 shows a simplified relationship using the example of the influencing factor of the degree of automation and the factory object of means of transportation.

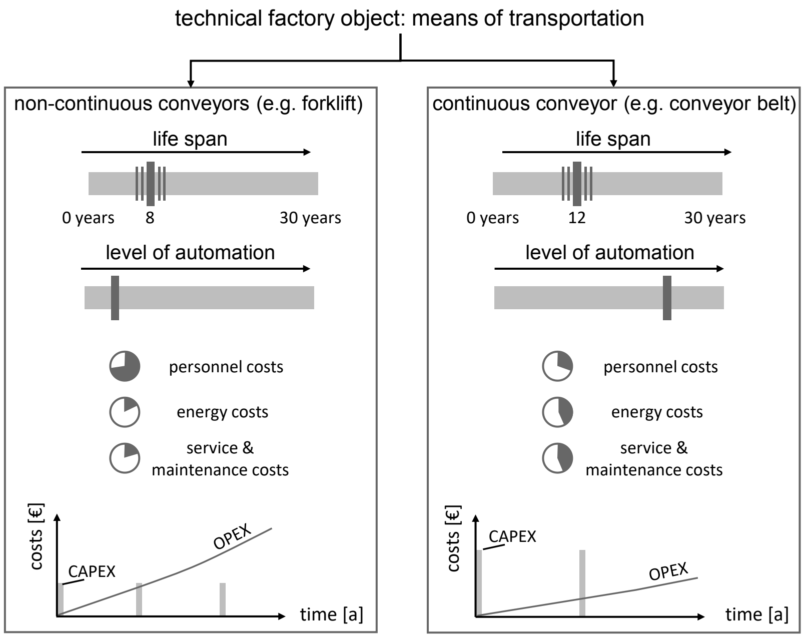

Figure 6: Exemplary configuration of the factory object means of transportation by the influencing factor degree of automation, own figure

Depending on product-side and process-side requirements, a decision can be made in a factory area in favour of a high degree of automation of the means of transportation, i.e. tending towards continuous conveyors, or a lower degree of automation, i.e. tending towards non-continuous conveyors. Although the superior group of continuous conveyors exhibits a higher potential for automation [84], it also requires considerably higher investments. The group of non-continuous conveyors [84] is characterised by a lower degree of automation and, thus, comparatively lower initial investment but higher operating costs. This is because the investment is generally higher for automated than manual systems [85]. The lifetime of the factory elements also influences the cost structure since, based on the lifetime, a supplementary or replacement investment becomes necessary in specific cycles over the life cycle. Overall, the degree of automation and the associated personnel requirements (in addition to, among other things, energy costs and maintenance costs) define a large part of the expected operating costs [86]. In the example shown in Figure 6, a simplified life cycle assessment concludes that a decision favouring a non-continuous conveyor is associated with lower initial investment but higher operating costs. A decision favouring a continuous conveyor based on life cycle costs depends on other factors, such as the product or the number of units. In general, the decision in favour of a particular configuration of a factory object also depends on the process requirements (see 3.1). For example, it may be the case that only certain factory sections, such as logistics, can be automated due to the complex process. Products with high complexity and low quantities could lead to only manual assembly over the life cycle being economical.

The consideration of different influencing factors enables different, future-oriented scenarios of factory design and the associated cost estimation over the life cycle as a basis for decision-making. The example above underlines the importance of considering influencing factors that configure the factory on a scenario basis via the factory elements and lead to different cost trends over the life cycle.

4. Conclusion and outlook

Factory planning projects are strategically important and capital-intensive projects with a long lifetime. Due to such projects' long-term and interdisciplinary character, the project cost estimate is essential. Incorrect cost estimates can lead to severe misinvestments. With current methods and tools, a holistic cost estimate is not or only insufficiently possible. Based on an intensive literature review, this paper identifies the research needs and requirements for a holistic approach to cost estimates for factory planning projects. Four essential requirements are identified and further analysed for a holistic approach. First, an approach must consider synergetic planning and costs from both a spatial and process view due to the interdependence of the two planning disciplines. Furthermore, the approach must be applicable in the early planning phase since costs can still be sufficiently influenced in this stage. In addition, in the context of a life cycle consideration, investments and operating costs must be estimated simultaneously due to their interactions. Finally, design-related influencing factors must be considered, which are essential in determining the factory design and, thus, the associated costs for scenario design. The methodically elaborated and detailed requirements are the basis for developing, in the next step, a holistic approach to cost estimates for factory planning projects in the early planning phase.

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