3rd Conference on Production Systems and Logistics

# Procedure Model For Dimensioning And Investment Cost Calculation In An Early Factory Planning Phase

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**Abstract**

Companies and their factories face constant change in today's world. Cost-intensive factory planning projects are being carried out in shorter intervals due to the increasing dynamism of the production environment. The related investments have a substantial impact on the liquidity of companies. Shorter production life cycles and changing consumer behaviour also require an adapted and more sustainable factory planning and cost estimation. However, especially in an early planning phase, available data and information are often uncertain and inaccurate. This effects in particular the outcome of the central dimensioning variables (operating resources, employees and area) for the planned factories. Incorrect dimensioning of these variables and thus of the associated costs can lead to substantial misinvestments. A holistic approach to obtain a reliable cost estimation of the factory project at an early stage is not yet available. This article therefore presents the development of a comprehensive procedure model for dimensioning and investment cost calculation in an early factory planning phase. For this purpose, relevant information and planning tasks with regard to dimensioning and cost estimation have to be identified first. Determined output values of the subsequent resource dimensioning represent the input values for the cost calculation. With the identification of surcharge factors, cost rates and calculation methods, the dimensioning variables, in particular the production area as the basis for the planned factory, can be estimated in terms of costs at an early stage.

**Keywords**

Investment cost calculation; procedure model; factory dimensioning; economic assessment; planning tool.

## 1. Introduction and problem definition

Factory planning can be described as a key factor for the economic success of companies [1]. Factory planning essentially involves planning the buildings, the production plant layout and the linking of the organizational units to each other including the material, personnel and information flow. Since factory planning lays the foundation for the entire production-side infrastructure, decisions in factory planning are often of a strategic and long-term nature. Accordingly, appropriate planning of different project contents is of essential importance for the manufacturing industry [2,3].

Due to their uniqueness and the complex positioning between cost, quality and time with often little or uncertain information, projects are generally subject to uncertainty [4]. Factory planning projects in particular represent a special challenge due to their long life cycle and significant investment costs. The early planning phase in factory planning projects plays a particularly important role. On the one hand, this is where the scope of action for each factory planning project is set [3,5]. On the other hand, the early planning phase presents planners with major challenges. Especially small and medium sized companies are lacking in sufficient resources, so that preliminary planning activities are lost in the operational business. In addition to that a reliable information database is missing [6]. However, reliable and accurate information are important basic conditions for factory planning projects [7]. In consideration of the fact that the cost influence is particularly high in the conceptual early planning phase and decreases with advancing planning progress, decision-supporting methods and approaches are especially relevant in an early phase [5,8]. Since the largest investments are determined at this point, it also means that the greatest influence on future project costs can be exerted at this early stage of planning [9]. This underlines the importance of economic efficiency assessments for decision support already at the beginning of the projects [5,9]. The dilemma of early factory planning quickly becomes apparent, since potential projects must be identified and selected with high uncertainties and inaccuracies without a secure planning basis and important economic assessments [10–12]. These uncertainties in the early planning phase significantly jeopardize the final economic planning of new factories [13]. If companies do not subject these projects to an appropriate assessment of economic efficiency, the risk of misinvestment increases, which in the worst case can lead to insolvency especially for small and medium-sized enterprises [14]. For this reason, it must be ensured that costs can be estimated at an early stage with sufficiently reliable data. Otherwise, there is a risk that calculations and reported costs are not sufficiently valid and thus damaging to the business [15]. In practice, these estimates are often based on individual experts and are thus subjective and insufficiently reproducible [6,16]. Various sources underline the omnipresent problem of finding suitable and practically applicable solutions to estimate costs despite high uncertainty in early planning phases [7,10,17,18].

Initial preliminary work has shown that feasibility studies [19] and digital planning tools [20] can address this problem and provide added value. These initial approaches detailed the problem and outlined possible solutions, but did not yet introduce a structured approach to solving the problem. The hypothesis of this paper is therefore that a procedure model for reliable cost estimation is required in early factory planning in order to provide companies with effective economic decision support in the context of factory planning. To achieve that, this paper first summarizes the necessary requirements for solving the problem and evaluates existing factory planning procedures and approaches with regard to the fulfilment of these requirements. Based on the resulting research gap, a procedure model is presented that provides an approach to close this research gap based on the identification of necessary planning information, early dimensioning of the variables operating resources, employees and area by including surcharge-based assessment of investment costs. Subsequently, a digital planning tool developed on the foundation of this work is presented, which supports the user in a structured and reproducible procedure in the selection of the right planning project.

## 2. Derivation of requirements and literature review

The introduction and statement of the problem lay the basis for the identification of requirements for a procedure model for dimensioning and cost calculation in the early phase of factory planning. Certain requirements are identified as follows:

- Consider planning cases
- Consider the early factory planning phase
- Dealing with uncertainty
- Calculation of planning variables (operating resources, employees, area)
- Derivation of investment costs
- Assessment of cost/benefit ratio for an advice

With these basic requirements, existing approaches will first be considered in order to derive potential research need. For this purpose, both the classic factory planning approaches and specific approaches that focus on uncertainty and the early planning phase were selected (Figure 1). Numerous procedures for factory planning exist in the literature and practice, including [1,2,5,9]. Several approaches have been summarized in the VDI Guideline 5200, which divides the planning process into seven different planning phases. This guideline reflects the interdisciplinary character of factory planning [24]. The classic factory planning process consists of sequential planning phases that lead from the "rough to fine" to a gradually detailed planning status [2,3]. The VDI 5200 combines the design of logistical and technological processes with the building planning according to the fees for architects and engineers [2]. Overall, a distinction can be made between the planning cases greenfield, brownfield, demolition and revitalization [24]. In addition, there are approaches, such as condition-based factory planning, which enable a parallel and modular factory planning procedure. Here, the aim is to design the planning process in a way that is adaptable to each specific application case [21–23]. Apart from the classic approaches, there are other procedures in the field of factory planning that deal in particular with uncertainty and early planning phases [6,25–27].

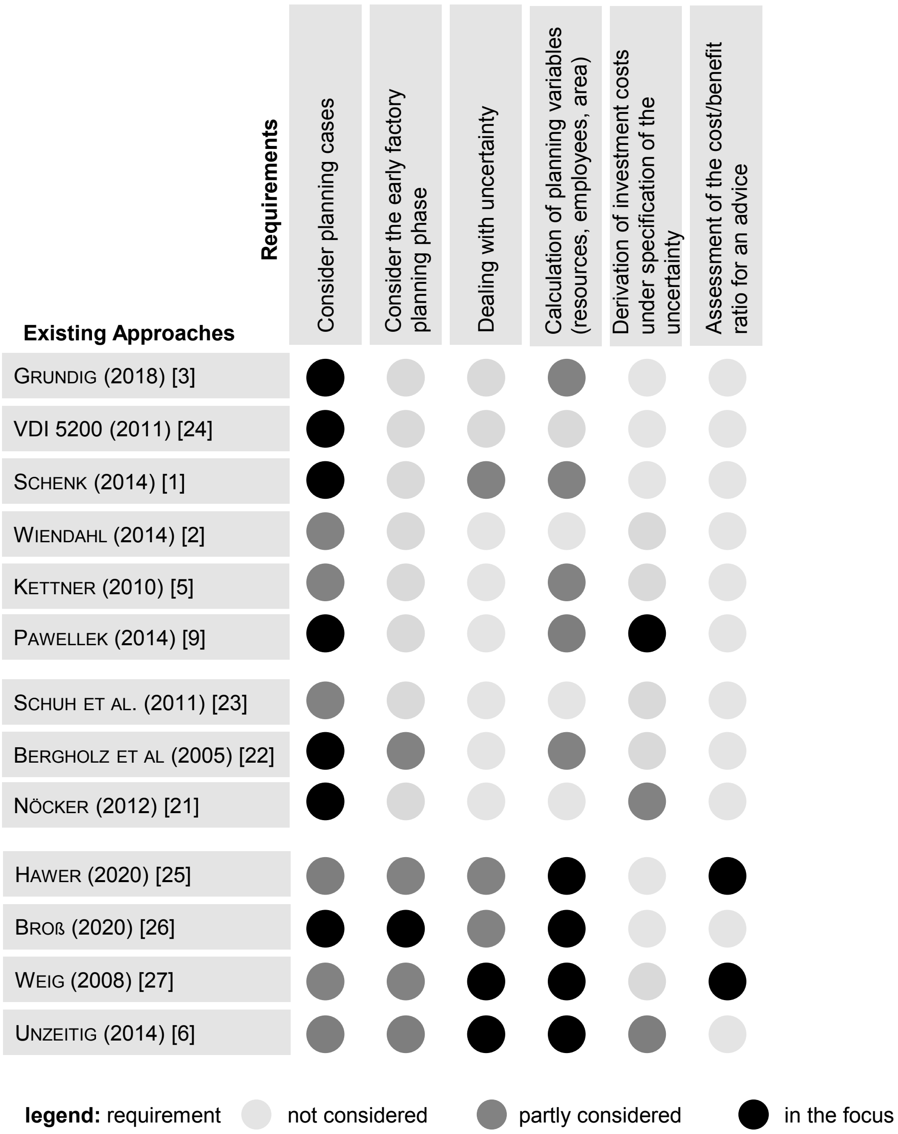


Figure 1: Assessment of factory planning approaches regarding identified requirements according to [19]

The classic literature often focuses on the procedure of factory planning itself as described in [1,3,24]. The factor uncertainty and the early planning phase are mentioned in the classic planning approaches, but neither GRUNDIG, KETTNER or SCHENK further elaborate on them, nor do they include them in their planning in advance. VDI 5200 and WIENDAHL only insufficiently name uncertainty associated with factory planning and accordingly do not address it further. Furthermore, the classic planning procedures only partially address the calculation of the basic dimensioning variables [1,3,9]. In PAWELLEK, however, the consideration of cost accounting can be emphasized [9]. The condition-based factory approach of SCHUH, BERGHOLZ or NÖCKER also only marginally considers the calculation of planning variables and the derivation of investment costs [21–23]. Uncertainty in the early factory planning phase is further considered by HAWER, BROß, UNZEITIG and WEIG. However, there are differences in the level of detail. HAWER uses a risk assessment analysis to identify the uncertainty factors [25]. BROß uses an approach with fuzzy logic and keeps this fuzziness also in his factors [26]. This also applies to WEIG, who partly uses expert estimates to make statements [27]. Ultimately, the approach of UNZEITIG can be highlighted, which successfully deals with uncertainty in detail, but in the end, similarly to the other approaches, does not provide a holistic approach to derive investment costs in an early planning phase [6].

Overall, the approaches only insufficiently link the requirements, especially the early planning phase, the dimensioning and the investment cost estimation derived from this. Specific approaches only consider single requirements and do not reflect upon the problem holistically. However, sub-points of individual approaches are considered useful and therefore will be included in the following elaborations.

## 3. Towards an approach for investment cost calculation in the early factory planning phase

On the basis of this background, a procedure model (Figure 2) was developed to dimension planned factories and to estimate their investment costs at an early stage. The developed model concentrates on the strategic planning cases greenfield and brownfield, since these two cases are most important for prospective adjustments of a factory. The entire procedure was developed by means of a three-stage research and analysis.

In the **first step**, planning tasks and planning information in the form of input and output parameters are considered in order to generally identify the required information for dimensioning and cost calculation in an early planning phase. Based on this, the main dimensioning variables (operating resources, employees, area) are described and appropriate calculation methods are derived in the **second step**. Due to the limited and uncertain data basis in the early planning phase, surcharge factors, cost factors and uncertainty factors are identified in the **third step** in order to be able to use them to perform an early cost estimate for the roughly dimensioned factory. The developed procedure model is developed in the manner that it can be used in an early planning phase at the very beginning of VDI 5200, where cost estimates are still insufficient or subject to a high degree of uncertainty (cf. Figure 2). By using process data as input parameters and including them in the calculation of the spatial view, the procedure model underlines the importance of synergetic factory planning to link production planning and building planning more closely. The individual steps taken to develop the resulting procedure model are explained in detail below.

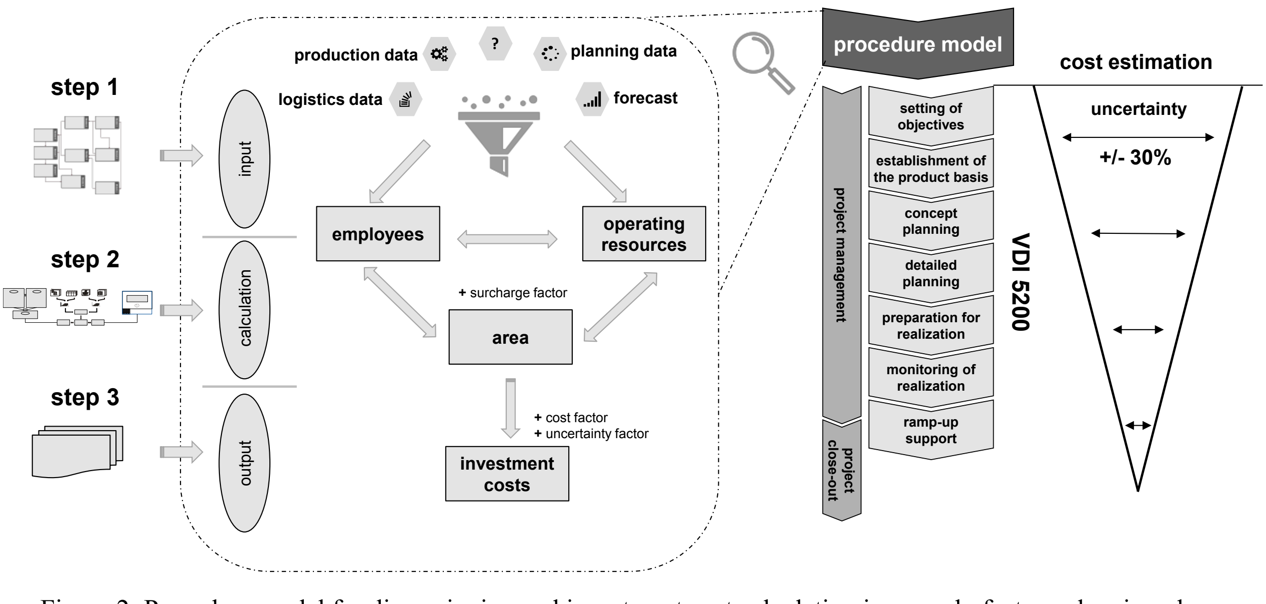


Figure 2: Procedure model for dimensioning and investment cost calculation in an early factory planning phase

### 3.1 Identification of planning information and planning tasks with regard to dimensioning

In order to dimension planned factories at an early stage, the required planning information and planning tasks first have to be defined. A common understanding has to be created concerning which information is available and at which point estimations may have to be made. For this purpose, a model (cf. Figure 3) was developed that describes in individual planning modules the procedure for dimensioning in an early planning phase.

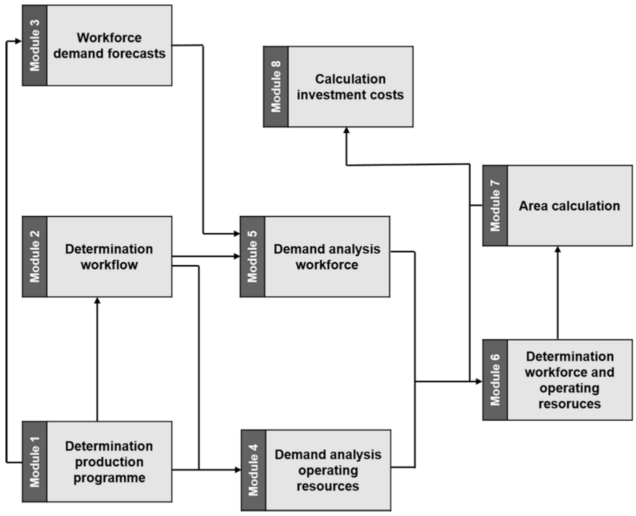


Figure 3: Step 1 - Identification of planning information and planning tasks in an early planning phase with regard to dimensioning

According to [23,25] the model consists of modules which have different input and output parameters within their planning tasks. In the early phase, for example, hardly any or no statements can be made about the material flow or detailed layout planning. In order to reduce structural complexity, this procedure was therefore limited to the basic dimensioning variables of operating resources, employees and area. Standard literature points out that these variables in particular should be taken into account in the early planning phase [2,3]. The first three modules "Determination production programme", "Determination workflow" as well as "Workforce demand forecast" serve to aggregate basic information regarding the three main dimensioning variables. Among other data, production programmes, sales forecasts, bills of materials, product variants, product characteristics, operating resource characteristics, work schedules and the organizational structure are analysed. The aggregated information from the first modules now serve as input parameters for the requirements analysis of operating resources and employees for the planned factory. With the assistance of a target/actual comparison of the available and required capacities, the requirements for employees and operating resources can thus be determined. These requirements in turn represent input information for the area calculation. Thus, area requirements for the planned factory are derived on the basis of the operating resources and employee requirements. The derived area is ultimately key input factors for the cost estimate in the course of the investment cost calculation. For this theoretically described procedure, calculation methods for dimensioning are now required that support the procedure and that are appropriate in the early planning phase.

### 3.2 Calculation methods for the key dimensioning variables of operating resources, employees and area

In the early planning phase of a factory, it is particularly important to consider the three main dimensioning variables of operating resources, employees and area. Due to this, these are briefly explained in this section, in order to subsequently derive and present adequate calculation methods (c.f. Figure 4).

The dimensioning variable **operating resources** is defined as technical work equipment for the fulfilment of a specific task in a work system. This technical work equipment is any "equipment (machines), plants, devices, measuring equipment, tools", which are used in a factory [3]. Their number and size with regard to the operating areas are of relevant importance for the development of a planning concept, especially with regard to the entire area programs. The type and number of operating resources required is largely defined by the respective product. For this purpose, demand figures (processing capacity) and availability figures (machine capacity) related to a specific period are compared with each other so that capacity deficits can be derived as a result, which form the basis for decisions on the dimensioning calculation of operating resources [3] (cf. Figure 4 according to [2]). Three possible outcomes can result from the comparison of the operating resources to the required demand of an already existing portfolio: A surplus, a shortage, and a balanced inventory [5]. From these correlations, measures for capacity adjustments can be derived, which have an effect on the dimensioning of the operating resources [2]. More detailed calculation methods for operating resources can be found in [3,5,28].

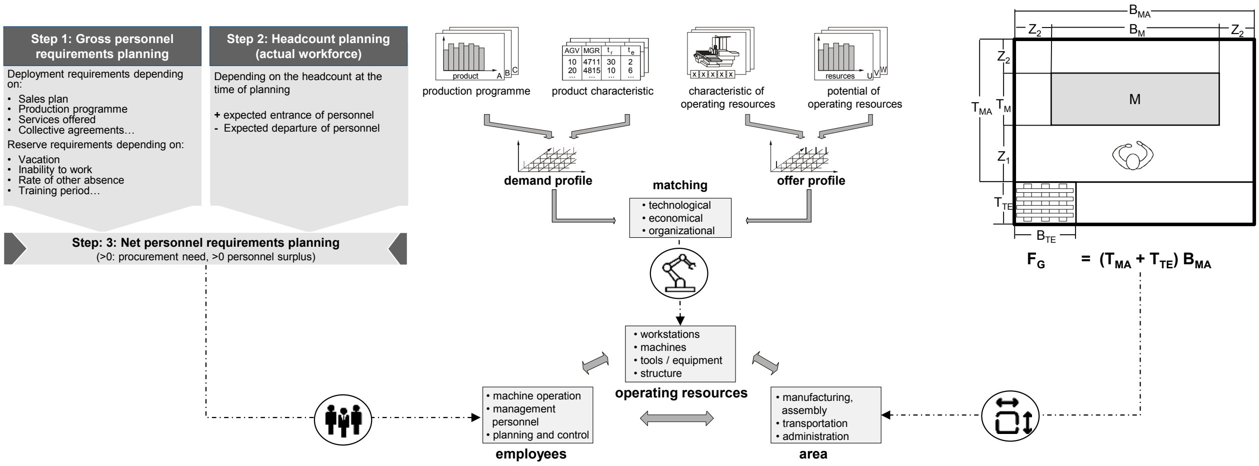


Figure 4: Step 2 - Calculation methods for the key dimensioning variables of operating resources, employees and area according to [2,29]

The dimensioning variable **employees** is determined by the number of workers required to perform all tasks in production and administration. The production programme is a useful reference point, as the corresponding demand is mapped and an estimate of the required number of workstations can be made [28]. In addition to the work areas, attention must also be paid to the installation of necessary functional rooms, such as toilets, showers and washrooms. The dimensioning variable employees can be derived from the required number of the workforce. A differentiated consideration of the number of personnel compared to the personnel requirements is necessary, which requires future changes in personnel planning. The planning of workforce requirements for a factory takes place in two ways, which should be carried out synchronously: On the one hand, qualitative personnel planning and, on the other hand, quantitative personnel planning [5]. The purpose of qualitative workforce planning is to match the required skills and knowledge of employees with the requirements of the work tasks [30]. It should be noted that companies are particularly restricted in short-term personnel planning by laws and collective agreement specifications. The required personnel demand has to be calculated for a future and long-term period and is mainly carried out for the areas of production, storage and administration in an early and rough planning phase [5]. Detailed calculation methods for employees can be found in [3,5,30] as well as in Figure 4 according to [29].

The **area** as the third dimensioning variable is mainly determined by the necessary area shares of the operating resources and the employees. Thus, the area becomes the central dimensioning variable, which also substantially determines the final layout of the building. According to VDI 3644, factory areas can be divided into main usable areas (especially production, storage and office areas) and secondary usable areas (in particular social areas and sanitary areas) as well as transport areas [31]. The determination of area requirements is considered to be an essential task of factory planning, as it attempts to adapt the design of areas to the necessary requirements for operating resources and employees. These adapted areas are realized in the layout and due to the usually limited available area supply, the available area must be constantly examined and reviewed for its active use with regard to the objective of maximum economic performance [3]. Detailed calculation methods for the area can be found in [2,3,5,32–34].

There are central interactions between the dimensioning variables, which makes a joint consideration essential. Thus, data and calculation results of the dimensioning of operating resources form the basis for individual area determinations, e.g. of the total machine working area. In particular, data regarding the dimensions and the capacity-related number of machines are crucial [2]. Figure 4 shows such a calculation-based dimensioning of the production area based on the actual machine footprint. In addition, the number of machines and the shift model determine the qualified employees required for the production process [2]. Furthermore, the degree of automation of the operating resources, for example, has an impact on the personnel requirements. In contrast, the introduction of a three-shift model ensures optimal utilization of the available capacities and equipment, but requires more personnel. Despite interactions between all dimensioning variables, changes in operation resources and personnel requirements always inevitably result in changes in area requirements. In the case of operating resources, it is the area reserved for the direct areas of the equipment and its periphery, and in the case of personnel for the indirect areas such as administrative areas or social areas. Since there is not enough information available at an early planning stage for the calculation methods outlined above, surcharge factors and cost as well as uncertainty factors in the dimensioning can provide useful assistance in the context of an investment cost estimate.

### 3.3 Identification and derivation of surcharge factors, cost factors and uncertainty factors

The results of the dimensioning are the basis for the final investment and cost decision [1]. The aim is to use a quantitative method to determine the profitable value of an investment from the given information and calculations. A summary of quantitative assessment methods for an investment can be found in [9]. However, due to the limited and uncertain data in an early planning phase, established and data-based cost calculation methods cannot be fully implemented. In order to still be able to provide a realistic picture of the planned factory in an early planning phase, surcharge factors, cost factors and uncertainty factors regarding the dimensioning of the area can be used. These are explained below in their practical application.

| surcharge factors | | |
|---|---|---|
| **production area** | | |
| surcharge operating area | 0,7m per operating resource | [33, 35] |
| surcharge safety distance | 0,3m per operating resource | [33, 35] |
| surcharge maintenance area | 0,6m per operating resource | [33, 35] |
| **transport and storage areas** | | |
| surcharge for path areas | 25% of production area | |
| surcharge for storage area | 25% of main usable area | |
| **secondary areas** | | |
| surcharge for office areas | 8-12m² per workspace | |
| surcharge for first aid room | 20m² | |
| surcharge for sanitary area | | |

| cost factors | | | |
|---|---|---|---|
| **type of building** | **usable area (€/m²)** | **volume(€/m³)** | **source** |
| factory building | 1171 | 137 | [36] |
| industrial production building (solid construction) | 1840 | 225 | [38] |
| industrial production building (skeleton construction) | 1390 | 185 | [38] |
| factory and warehouse building | | | [37] |

Figure 5: Step 3 - Identification and derivation of surcharge factors, cost factors, and uncertainty factors

First of all, valid area surcharge factors were identified depending on the operating resources and the employees in accordance with DIN 3644 for both the direct and the indirect areas. In the direct area, in addition to characteristic values regarding the machine dimensions, additional factors for individual area dimensions are important reference values, which allow a reasonable estimation of the total area. These supplements are, among others, values from the workplace guidelines (among others [35]) and are required in order to be able to carry out unproblematic operation, compliance with safety distances or necessary maintenance work. Commonly used methods in practice are the functional area calculation and the substitute area method in order to calculate the total production area on the basis of the machine base area with the help of surcharge factors (see also chapter 3.2). In addition, experience has shown that 25% of the production area can be allocated to path and transport areas [2]. In the indirect areas, the workplace guidelines and empirical values for surcharges in the area of offices and social areas are dependent on the number of employees. On the left, Figure 5 shows an excerpt of aggregated surcharge factors for calculating area space as a function of the dimensioning variables employees and operating resources.

In the final step of the procedure model, the area is included as a central input parameter in the investment cost estimate. Here, cost rates from various institutions that regularly analyse the cost structure of the construction industry are taken into account. The Federal Statistical Office, for example, presents the average costs at the time of approval of industrial buildings in its annually published reports on building permits [36]. Other sources [37,38] classify further cost rates and cost groups according to DIN 276 [39] on the basis of continuous random samples of new buildings. Depending on the required absolute area, the investment costs can now be estimated with these cost factors. It is possible to differentiate cost factors according to the construction method (skeleton construction, solid construction), construction quality (light, heavy) and depending on the required functionalities of direct and indirect areas. Cost factors for cleanrooms, for example, are many times higher than standard areas for industrial requirements. Figure 5 shows a section of possible cost factors on the right-hand side. These numbers represent general reference values from practice, which may differ with regard to the industry and company-specific requirements.

Cost estimates are increasingly subject to uncertainty due to the turbulent market environment. Since it is often not possible to calculate the exact requirements for the planned factory and, for example, the fluctuation of raw material prices or cost increases for technical building equipment validly in an early planning phase, uncertainty factors are often included in the investment cost calculation in practice. The data and information in this early planning phase are insufficiently accurate for exact calculations. Therefore, a variable uncertainty factor of 25-30% is added to the factory investment costs calculated in this procedure model. This factor represents a proven average value from practice [40–42].

### 3.4 Integration of the procedure model into a digital planning tool

The preliminary work and the developed process model support the dimensioning of factories in the planning phase at an early stage as well as its economic assessment. Surcharge, cost and uncertainty factors provide a solution in so far as information is often not yet completely available in an early planning phase. This procedure needs to be supported by a software tool in order to be able to carry out the dimensioning and estimation in a structured and reproducible way. The use of digital planning tools generally enables planning errors to be reduced and planning time to be cut while quality is increased [7,43]. Furthermore, the use of computer-aided tools can also contribute to mastering the complexity in the planning process [43]. Therefore, in parallel to the presented process model, a digital planning tool is developed that supports the user in a structured procedure and thus represents a reproducible decision support for the selection of the right planning project. In this context, the software-based cost calculator should also help to enable the early estimation of investment costs for planned factories for a wide range of users. Furthermore, by entering different input parameters, different scenarios for the future factory can be calculated and compared with each other. In this context, the main dimensioning variables are calculated according to the procedures and surcharges outlined above. On the basis of the calculated areas, investment costs for the individual factory areas can then be calculated.

## 4. Conclusion and Outlook

In a turbulent and uncertain market environment, factory planning with its interdisciplinary character becomes a complex and permanent task. In order to avoid misinvestments, planned factories should be subjected to a cost efficiency assessment at an early stage. However, in an early planning phase, information is often uncertain or not available. This paper therefore presents a procedure model that supports dimensioning and investment cost calculation in an early planning phase. In a three-stage procedure, planning information and tasks for the early dimensioning of factories are identified, calculation methods for the central dimensioning variables of operating resources, employees and area are derived and the resulting investment costs are estimated on the basis of surcharge, cost and uncertainty factors. To reduce complexity, a digital planning tool supports the user to estimate investment costs in a reproducible procedure and thus make future-proof decisions for the company. There is a need for further research in a more detailed consideration of uncertainty, e.g. with the aid of fuzzy logic, in order to take even closer consideration of the early planning phase. In addition, the interactions between the dimensioning variables have to be analysed in more detail in order to obtain a reliable planning basis for the subsequent cost calculation. Furthermore, certain target fields of factory planning, such as changeability or sustainability, could be integrated into the process model in order to be able to estimate the resulting investment costs for various scenarios.

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