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Analytical model for determining the manual consolidation time for large equipment manufacturers

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Abstract

Large and complex products such as aircrafts or wind energy plants are usually produced in small batches. This leads to particular requirements for logistics with regard to process efficiency, flexibility and reliability as well as coordination and control of the processes. In practice, the consolidation of parts from different storage areas is a labour-intensive process, which must be considered in the planning or remodelling of warehouses. This work presents an analytical model to determine the consolidation time within a single formula at an early planning stage. Within this formula transport, handling, base and allowance times are considered. Finally, the analytical model is applied in an industrial project which deals with the new planning of warehouses for a large equipment manufacturer. The presented work connects academic approaches for calculating the commissioning time with practical experiences gained in industrial projects. Researchers benefit from this work, as practical considerations and corresponding solutions are pointed out and insights into practical projects are given, while logistics planners could benefit by applying the developed model.

Keywords

Logistics planning; Consolidation; Analytical model; Large equipment manufacturer

1. Introduction

Personnel costs often dominate the proportion within the cost structures of a warehouse. The calculation of logistics personnel is therefore an essential component in the planning of warehouses or the remodelling of logistics processes. The commissioning process, i.e. the combination of subsets from a total quantity of goods on the basis of requirements [1] is a labour-intensive process, due to the high complexity in material handling. In particular for large equipment manufacturers, manual handling and transport of goods is common, due to low production rates and high requirements for flexibility [2]. Consolidation describes a part of the commissioning process that serves to merge goods, picked from several storage systems.

Especially at an early planning stage, the planning data base is often insufficient for a precise calculation of the required consolidation personnel [3]. During the course of a warehouse planning project for a large equipment manufacturer, the need for a model to calculate the effort in consolidation became apparent. Hence, an analytical model of manual consolidation processes was built and subsequently applied in order to compare different storage scenarios as part of the planning project. The model extends the established considerations for commissioning, as formulated by ten Hompel [4], among others. The particularity of the model consists in process-specific adaptions and simplifications for the consolidation process of large equipment manufacturers, resulting in a single equation for the calculation of the consolidation time.

The paper is structured as following. The requirements on the commissioning process and in particular on the consolidation process for large equipment manufacturers are described in section 2. Subsequently, section 3 briefly describes the state of the art, puts the model into context and points out gaps in the present literature. The analytical model is presented in section 4 and the exemplary application during the planning project is described in section 5. The paper closes with a conclusion and an outlook on future works.

2. Requirements and description of the commissioning process

The production schedules of large equipment manufacturers are determined by a large variety of variables, which are often hardly predictable and difficult to combine in the operative production and logistics processes [5]. The dependency on delivery schedules, the availability of labour and technical resources as well as multiple production stations with diversified functions require efficient and responsive logistics processes [6]. Due to production structures demanding for geometrical diversified parts in small batch sizes, the logistics department must offer high flexibility in its processes and storage systems [7]. Consequently, manual labour is common.

As exemplary depicted in Figure 1, the process of commissioning is initiated by the placement of work orders based on the production schedule containing articles from several article families stored in different storage systems. First, the required parts for a work order are picked from a storage system. Therefore, several storage systems containing different article families, such as shelving racks for standardized storage boxes or honeycomb racks for long goods, need to be addressed by specific picking orders. Inside the storage systems, the parts are picked and aggregated to collection units. During this process, labour is required to pick the requested parts from the storage system and to perform additional handling steps like repacking and labelling of the parts [4]. After completing the steps of the picking process, the finalized collection units must be transferred to their designated consolidation buffer. Subsequently, the ordered articles need to be consolidated as shipping units in predefined load carriers and delivered to the corresponding work station in the production [8].

The consolidation process of the collection units is initiated when all units required for a specific work order are finalized and available at the respective consolidation buffers. The outcome of the considered consolidation process is a shipping unit which merges all collection units from the addressed storage systems

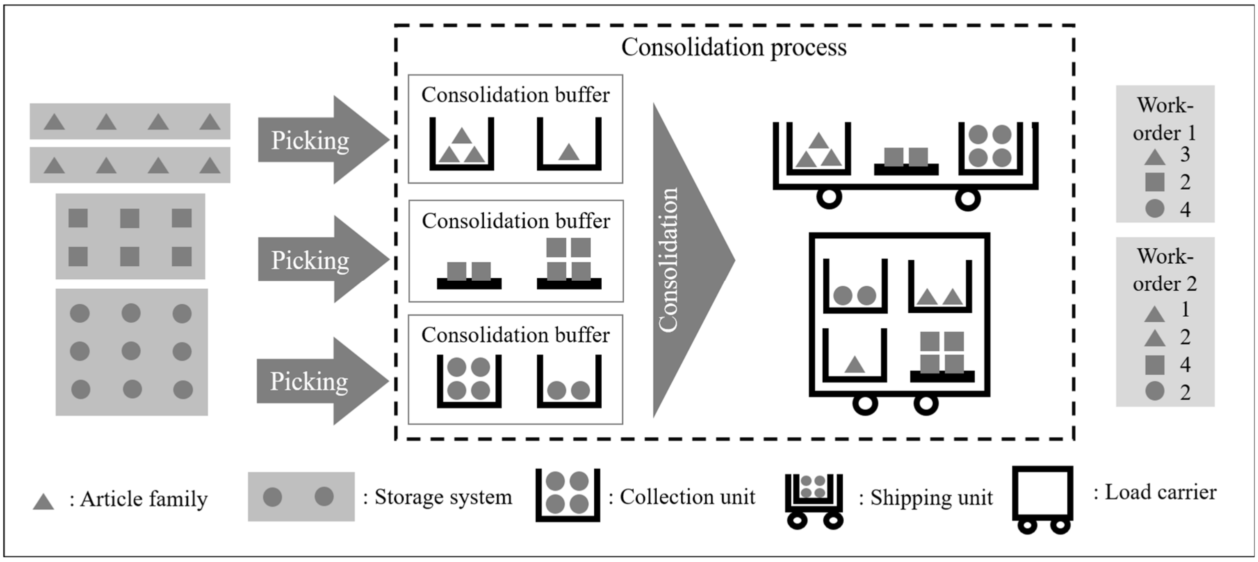

Figure 1: Consolidation of shipping units according to work orders.

to a single load carrier per work order. The appropriate load carrier is predefined depending on the geometric structures of the collection units in order to optimize material transport or handling. After setting up the load carrier, an employee in the consolidation area starts walking to all consolidation buffers storing collection units for the current work order. At every consolidation buffer the required collection units must be searched and placed safely and efficiently on the load carrier. After gathering all collection units, the employee must complete the load carrier by performing additional steps like printing labels for the work station in the production and finally bringing the shipping unit to the dispatch area. At this point the consolidation employee is available to process the next work order.

3. State of the art and revealed gaps

The calculation of the required personnel is part of every production and logistics planning method. Established planning methods by Wiendahl [8], Kettner [9], Grundig [10] and VDI guideline 5200 - part 1 [11] exist among others. The methods can be clustered into four phases: project setup, structuring, system design and realization. The aim of the structuring phase is to create a holistic concept of the planning object [3]. An important part of this planning phase consists in the determination of personnel requirements, which are further detailed in the structuring phase. A commonly applied way of calculating the personnel requirements consists in the determination of the overall work effort (time requirements per work unit) of all manual activities [10]. Therefore, the manual activities need to be defined and their time requirements quantified. Established analytical methods for calculating commissioning efforts are given by Martin [12], Gudehus [13] and ten Hompel [4]. The named authors split the commissioning time into *base time*, *transport time*, *handling time* and *dead time* as illustrated in Figure 2. In VDI 4481 [14] the component *allowance time* is included to consider performance lowering factors such as work interruption for distractions or disturbances.

Ten Hompel [4] describes the processes and the analytic calculation of the commissioning time for different processes such as conventional person to goods commissioning, commissioning on the high rack or the commissioning on an Automated Storage and Retrieval System (ASRS). The calculations are based on average working times per part position for all named components of the commissioning time. The process of conventional person to goods commissioning is partly analogous to the considered consolidation process described in section 2. However, rather than walking along the aisles of a shelving system, the employee moves along the transport routes in the warehouse to merge collection units from the consolidation buffers instead of the picking units from a storage location.

From the particularities of the process described in section 2 arise special requirements for the calculation of the commissioning time, which cannot be fully satisfied by the given methods. First, the considered process is not analytically described in the common literature. The existing methods therefore need to be adapted to the described consolidation process. Second, for large equipment manufacturers the determination of average values per collection unit is difficult. The planning database is often inadequate and characterized by many uncertainties in particular at an early planning stage [3]. A detailed calculation of the

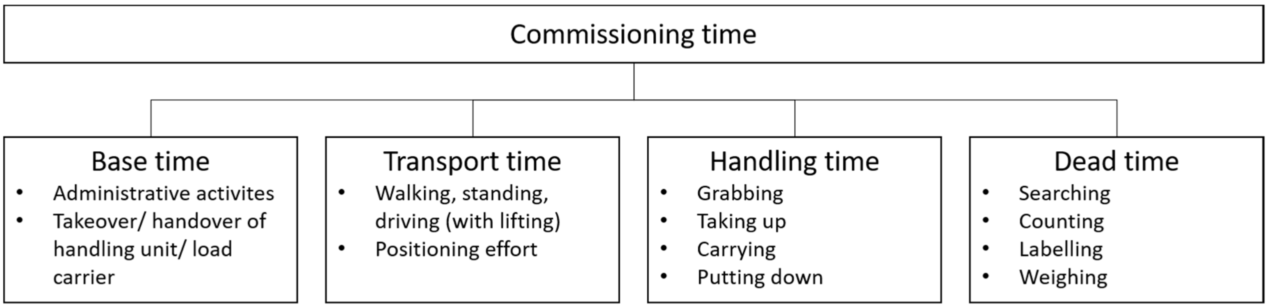

Figure 2: Division of commissioning time according to Martin [13], Gudehus [14] and ten Hompel [4].

commissioning time is often not feasible or necessary at an early stage of planning. In order to calculate the approximate consolidation time, assumptions and simplifications have to be included into the model. As an example, the transport time for acceleration and deceleration due to manual transports over long distances is very low for the given process and can therefore be neglected. As the process times of the components of the consolidation time are highly varying for large equipment manufacturers, the use of average workloads per collection unit limits the comprehensibility of the calculation and therefore the potential for identifying optimization measures. Furthermore, the division of the handling time or dead time into process steps, such as labelling or carrying, require a detailed description of the processes, which are in practice usually not defined at an early planning stage. This detailing rather takes place later as part of the system planning. A fine-grained calculation model is therefore not appropriate at an early planning stage.

4. Analytical model for calculating the consolidation time

For the analytical model the process described in section 2 is considered. Consolidation orders are not triggered until the required collection units are placed into the consolidation buffers. In order to calculate the distances for transportation the layout has to be previously defined. Furthermore, the approximated work order data are required for a representative time period. The larger the chosen period the more accurate is the model. The recommended minimal time period is depending on the dynamics of the production structure. At this stage of planning it is also possible to use estimated values in order to receive first results as an approximation. To determine the time components of the respective processes, time recordings from already existing commissioning systems can be used. A table with a brief description of all the used variables for the analytical model can be found in the appendix.

To reduce the complexity of the model the **consolidation time** can be calculated per individually defined time interval. Therefore, the calculation of average values per position for the components of the consolidation time can be avoided. The calculations for the components are simplified according to the considered process and compromised in a single formula. The consolidation time (t_{consol}) is the result of the sum of the total transport time ($t_{transport}$), handling time ($t_{handling.}$), base time (t_{base}) and allowance time ($t_{allowance}$) for the defined time interval. The handling time thereby includes the dead time. The allowance time is usually given in percent by the efficiency factor (x_e) of the system. The equation for the consolidation time is

$$t_{consol} = \Bigg(\underbrace{v \sum_{j=0}^{n+1} \sum_{i=0}^{n+1} d_{ij} \cdot t_{ij}}_{t_{transport}} + \underbrace{\sum_{i=1}^{n} c_i h_i}_{t_{handling}} + \underbrace{\sum_{wo=1}^{k} b_{wo}}_{t_{base}} \Bigg) \cdot \underbrace{(1 + x_e)}_{efficiency} \tag{1}$$

whereby the individual components of the equation are described below.

The **transport time** for each transport can be calculated as the distance travelled (d) divided by the average velocity (v). To calculate the total transport time per time interval, the obtained value needs to be multiplied with the amount of transports (i) per given time interval. As previously described the considered consolidation process consists of the manual merging of collection units from several consolidation buffers. The consolidation buffers are indicated from 1 to n. The starting point to pick up the empty load carrier is indicated by 0 and the handover point for the shipping unit by $n + 1$. For each route from point i to point j

the travel distance (d_{ij}) and the transport intensity (i_{ij}) are entered into the separate matrices D and I, resulting in

$$t_{transport} = \frac{1}{v} \sum_{j=0}^{n+1} \sum_{i=0}^{n+1} d_{ij} \cdot i_{ij}, \tag{2}$$

$$\text{with } D = \begin{pmatrix} d_{00} & \cdots & d_{0n} \\ \vdots & \ddots & \vdots \\ d_{01} & \cdots & d_{nn} \end{pmatrix} \text{ and } I = \begin{pmatrix} i_{00} & \cdots & i_{0n} \\ \vdots & \ddots & \vdots \\ i & \cdots & i_{nn} \end{pmatrix}.$$

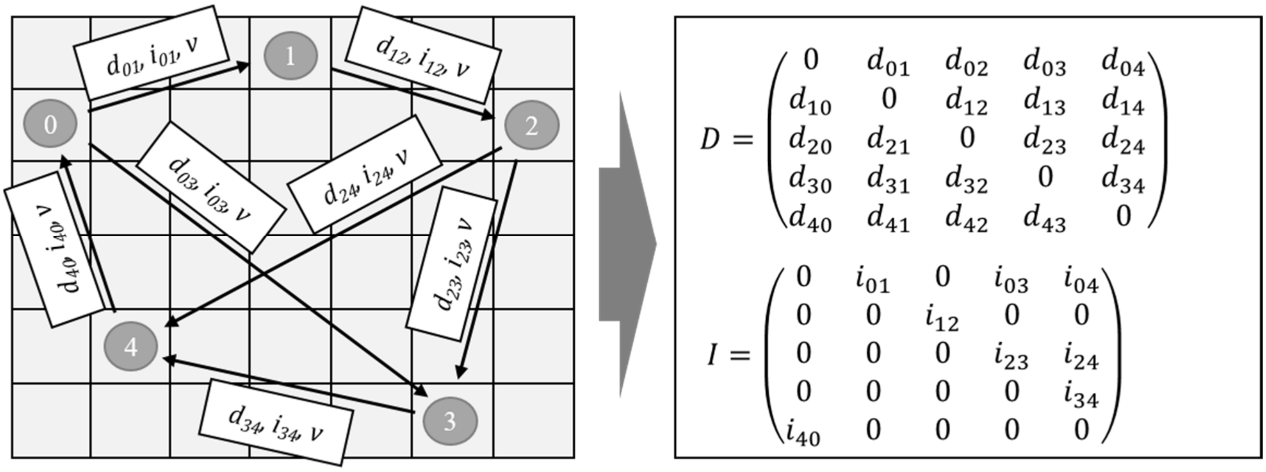

Figure 3: Transportation routes for the consolidation process and the derived matrix structure.

Exemplary, the transport process with its parameters and the derived matrices are illustrated in Figure 3. The distance D can be inferred from the layout, while I can either be estimated or concluded from existing work order data. Since only manual transport is considered, the velocity of the picker is assumed to be constant regardless of the route section. Acceleration and deceleration can be neglected for manual transport. Commonly a value between 0,8 m/s and 1,1 m/s is assumed for walking velocity.

In the presented model the dead time is included into the **handling time** per time interval. The selected time interval has to correspond to the considered unit for the transport time. The time for handling mainly differs depending on the physical time components such as for grabbing or putting down of the collection units. As described in section 2, an article family, e.g. small parts, long or pallet goods, is commonly stored, each in an appropriate storage system. Therefore, consolidation buffers usually contain similar collection units. As a reasonable assumption at an early planning stage, the handling time for the merging of a collection unit (h_i) is mainly depending on the consolidation buffer 1 to n. The handling time for merging all collection units during the chosen time interval from a certain consolidation buffer onto different load carriers is given by the amount of collection units to be merged from each consolidation buffer (c_i) times the handling time per collection unit (h_i), resulting in

$$t_{handling} = \sum_{i=1}^{n} c_i \, h_i \tag{3}$$

$$\text{with } \vec{c} = \begin{pmatrix} c_1 \\ \vdots \\ c_n \end{pmatrix} \text{ and } \vec{h} = \begin{pmatrix} h_1 \\ \vdots \\ n \end{pmatrix}.$$

Figure 4 exemplary illustrates the handling process and the components of the given equation. To merge the collection units of work order 2 onto a common load carrier four collection units need to be handled, whereby two of the collection units are merged from consolidation buffer 1. To calculate the total handling time for both work orders 1 and 2 the single handling times h_i need to be summed up as

$$t_{handling} = \sum_{i=1}^{n} c_i\, h_i = 3\, h_1 + 2\, h_2 + 2\, h_3.$$

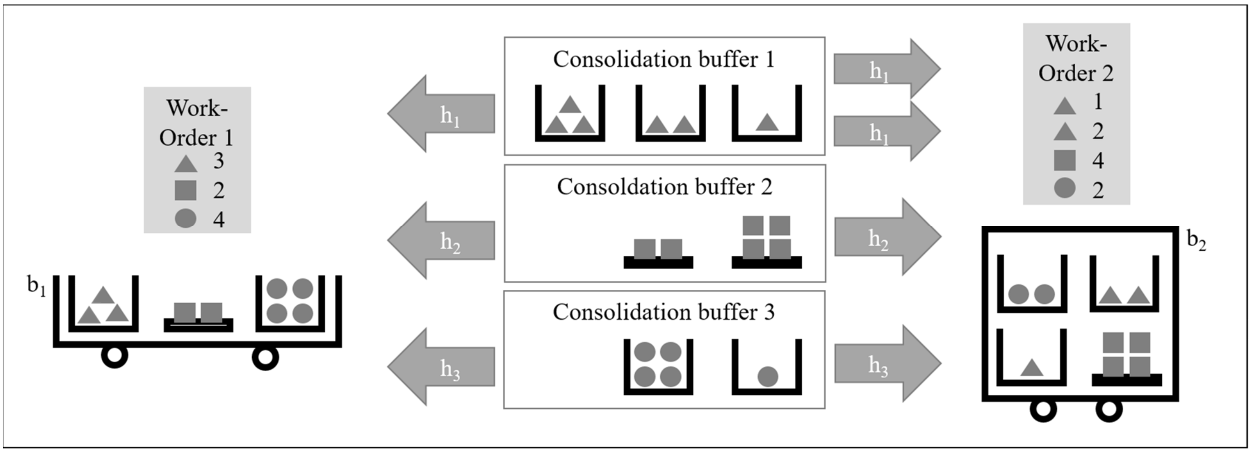

Figure 4: Handling time for the consolidation process.

The **base time** consists of administrative and manual activities related to take over or hand over of the load carrier. Since a consolidated load carrier builds the work order in the considered process, the total base time t_{base} per time interval is the sum of the base times b_{wo} for all work orders ($wo = 1 \ldots m$). In a production providing consolidation process as described in section 2 different types of load carriers, e.g. pallets, roll cages or special load carriers are used. As a simplification it can be assumed that b_{wo} is identical for the same type of load carrier. The formula for the base time is therefore given by

$$t_{base} = \sum_{wo=1}^{m} b_{wo} \quad \text{with} \quad \vec{b} = \begin{pmatrix} b_1 \\ \vdots \\ b_m \end{pmatrix}. \tag{4}$$

The **efficiency factor** x_e can either be chosen by standard values or on the basis of time measurements of existing logistic processes.

5. Application of the developed model in a warehouse planning project

The developed model was applied as part of a warehouse planning project for a large equipment manufacturer. The aim of the project was to store highly varying types of goods in a centralized warehouse in order to supply the production efficiently with a high flexibility, reliability and responsiveness. The total warehouse area is about 40.000 m^2. The considered parts from the warehouse are picked from several storage systems, consolidated on the appropriate load carriers and pushed to the production. In the production the load carriers are buffered and pulled to 20 different work stations on the assembly line.

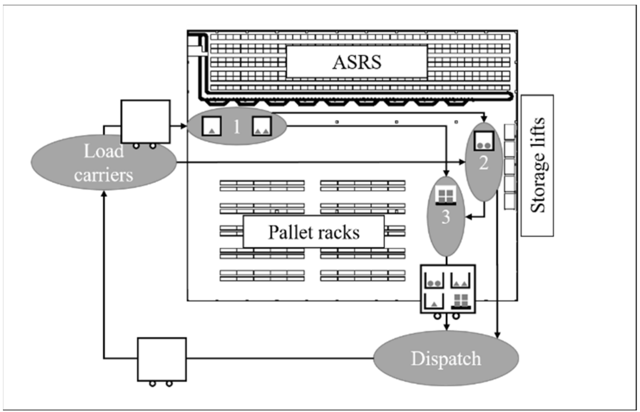

Figure 5: Layout and consolidation process for the considered storage scenario.

For the evaluation of different storage scenarios, the total investment and operational costs had to be calculated as part of the concept planning under a high uncertainty of the planning data. The scenarios were consisting of different combination of storage systems for storing small part containers, long goods and pallet goods including the processes for put away, picking and consolidation. Depending on the scenario the personnel costs make up a dominant part of 70 % to 90 % of the total costs for 10 years. The calculation of the consolidation time according to the developed analytical model is exemplary stated for the following scenario: Small goods are stored into an ASRS, long goods in storage lifts and pallet goods in pallet racks. Figure 5 shows a reduced section of the proposed layout and depicts the affiliated consolidation process. Goods from the ASRS are picked into containers. Subsequently these containers are transported back automatically into the ASRS to be temporarily stored for buffering. The containers can be retrieved from the system when needed and automatically be transported to consolidation buffer 1. The goods from the pallet racks are picked by forklift and transported to consolidation buffer 2. The long goods are picked directly from the storage lifts to the shipping unit load carrier. Long goods can therefore already be seen as a collection unit and the storage lifts as consolidation buffer 3. Table 1 summarizes the scenario by affiliating the article families with their dimensions to the storage system and their number of storage locations.

Table 1: Overview of the considered storage scenario.

Article family	**Dimensions**	**Storage System**	**Storage Locations**
Small parts	Container < 600 x 400 x 220 mm	ASRS	40.000
Long goods	1200 mm < Length < 1800 mm	Storage lift	5.000
Pallet goods	Packages < 800 x 600 x 500 mm	Pallet rack	3.000

For each product 57 differently composited shipping units are needed, which comprise one or more types of article families. The transport order and distances were concluded from the layout. As all transports are carried out manually by walking, the transport velocity is assumed to be constant with $0{,}9\ \frac{\mathrm{m}}{\mathrm{s}}$. In order to set up matrix I the composition of the 57 load carriers was considered. The exact composition varies due to customization of the product, but the contained article families and therefore consolidation buffers, that need to be visited are consistent. Each month around 160 products are completed, thus 8 per working day. The time interval for the calculation of the consolidation time was chosen to be one working day. The values for calculating $t_{transport}$ are given as

$$D = \begin{pmatrix} 0 & 50 & 75 & 85 & 110 \\ 50 & 0 & 25 & 35 & 60 \\ 75 & 25 & 0 & 10 & 35 \\ 85 & 35 & 10 & 0 & 25 \\ 110 & 60 & 35 & 25 & 0 \end{pmatrix} \text{m} \quad \text{and} \quad I = 57 \cdot 8 \begin{pmatrix} 0 & 0{,}8 & 0{,}15 & 0{,}05 & 0 \\ 0 & 0 & 0{,}7 & 0{,}1 & 0 \\ 0 & 0 & 0 & 0{,}6 & 0{,}25 \\ 0 & 0 & 0 & 0 & 0{,}75 \\ 1 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{5}$$

$$\text{and} \quad v = 0{,}9\,\frac{\text{m}}{\text{s}}.$$

In average there are about 700 small parts containers, 32 long goods and 147 pallet goods required from the planned warehouse for each product. The *handling times* h_1, h_2 and h_3 per collection unit for the consolidation buffers 1, 2 and 3 were determined from time measurements in similar processes. The handling time h_2 is particularly high, due to the waiting time for the plateaus from the storage lift. The components of formula (3) are given by

$$\vec{c} = 8 \cdot \begin{pmatrix} 700 \\ 32 \\ 147 \end{pmatrix} \quad \text{and} \quad \vec{h} = \begin{pmatrix} 10 \\ 70 \\ 40 \end{pmatrix} \text{s}. \tag{6}$$

The four different types of load carriers (roll cages, special pipe carriers, special load carriers and pallets) are used in the consolidation process. The base time per load carrier was determined by tests while the efficiency factor x_e of 20 % was taken from an analysis according to REFA [15] conducted in another warehouse. The components of formula (4) are given by

$$t_{base} = 8 \cdot \sum_{1}^{57} b_{wo} \quad \text{with} \quad \vec{b} = \begin{pmatrix} b_{cage} \\ \mathrm{b}_{long} \\ b_{cage} \\ \vdots \\ b_{pallet} \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} b_{cage} \\ \mathrm{b}_{pipe} \\ b_{special} \\ b_{pallet} \end{pmatrix} = \begin{pmatrix} 30\,\text{s} \\ 50\,\text{s} \\ 70\,\text{s} \\ 50\,\text{s} \end{pmatrix}. \tag{7}$$

The consolidation time per day was calculated by inserting the components from the equations (5), (6) and (7) into (1). Figure 6 shows the time shares according to the components of the consolidation time. The resulting consolidation time is 60 h. Considering seven hours work shifts, 9 workers per day are required as the operational team for consolidation. The biggest share of the consolidation time consists in the handling time. The base time, at 2 %, represents a comparatively small proportion. It is therefore expected that the greatest potential for optimization lies in a reduction of the handling time. Consequently, the application of modular load carriers according to Sliwinski [6] in order to reduce repacking efforts and work order optimized put away strategies for storage lifts according to Nicolas [16] could be identified as the main optimization measures.

6. Conclusion and outlook

The consolidation of work orders for large equipment manufacturers is a highly manual and labour-intensive process, which is characterized by high requirements on flexibility and responsiveness. Experiences from industrial projects revealed the demand for a mathematical model to calculate the consolidation time regarding the process-specific particularities and conditions of logistics planning projects at an early planning stage. An analytical model based on the calculation of transport, handling, base and allowance times was presented and subsequently applied during an industrial planning project for a large equipment manufacturer in order to evaluate different storage scenarios. The determination of the required planning data was based on analyses of the warehouse and work order structures as well as time recordings of already existing commissioning and test systems. The applicability of the model was successfully proven. In order to validate the presented model, simulations of calculated commissioning process are currently being carried out. Subsequently, empirical data will be recorded once the warehouse is in operation. The model will be applied in future projects in order to further validate it.

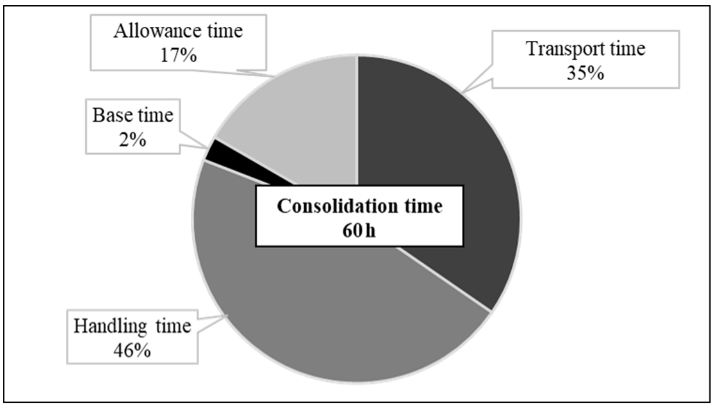

Figure 6: Shares of time components of the calculated consolidation time.

Appendix

Table 2: Table of symbols.

Symbol	Description	Unit
$\vec{\boldsymbol{b}}$	Vector containing base times required per work order 1 to m	-
$\boldsymbol{b_{wo}}$	The base time required per work order	s
$\vec{\boldsymbol{c}}$	Vector containing amounts of collection units to be merged from consolidation buffer 1 to n	-
$\boldsymbol{c_i}$	Amount of collection units to be merged from each consolidation buffer per chosen time interval	-
$\boldsymbol{d_{ij}}$	Distance from point i to point j	m
$\vec{\boldsymbol{h}}$	Vector containing handling times per collection unit from consolidation buffer 1 to n	-
$\boldsymbol{h_i}$	Handling time required per collection unit	s
$\boldsymbol{i_{ij}}$	Transports from point i to point j per chosen time interval	-
m	Amount of work orders per chosen time interval	-
$\boldsymbol{n}$	Amount of consolidation buffers	-
$t_{allowance}$	Allowance time for work interruptions per chosen time interval	s
t_{base}	Base time for preparing the consolidation process for a chosen time interval	s
t_{consol}	Consolidation time for the consolidation process per chosen time interval	s
$t_{handling}$	Handling time for the merging of collection units per chosen time interval	s
$t_{transport}$	Transport time during the consolidation process per chosen time interval	s
v	Average walking velocity of the consolidation employees	m/s
$\boldsymbol{x_e}$	Performance factor to consider factors such as work interruption for distractions or disturbances	%

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Biography

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