Development of New Method for Choosing Standard Components Subject to Minimal Cycle Time and Minimal Sum of Purchasing Cost

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Abstract. An assembly line is made from different machines and a machine can contain different stations and function carriers. Each function carrier even is performed by different standard function carrier variants. The designer can calculate and select the available function carrier variants to construct into a new machine. The advantages of using the available function carriers are the low cost, reduction of design and manufacture time and improvement of machine working life. If a machine has n function carriers, each function carrier contains m variants. Hence, there are n^m combinations to make the machine. The number of these combinations increase rapidly according to a large number of function carriers. To select the suitable function carrier variants subject to optimal cycle time and total purchasing cost, the designer cannot manually select the best solution from so many options. Nowadays, there is no effective method to solve this problem. To solve this problem, this paper will set up the operating cycles for an assembly machine and establish linear optimization in standard form for choosing the best function carrier variants from the given database. To minimize both the cycle time and total purchasing cost of an assembly machine, the linear programming must contain two stages and run in sequence. The large linear optimization is programed and solved by using the IBM ILOG CPLEX Optimizer. The optimal results will be exported to tables in a database. This makes the designer easy evaluate and select the best solution. In addition, designer can expand the scope of study to design other machines.

Keywords: Assembly machine · Cycle time · Function carrier · Linear optimization · Standard component · Total purchasing cost

1 Introduction

1.1 Compensation of Cycle Time

The product portfolio of numerous companies, such as Schunk, Zimmer Group, Festo or Bosch etc., includes standardized components with technical data, which are stored in catalogues or databases. These data mainly include dimensions, load capacities, repeat accuracy, speeds and accelerations as well as possible cycle times [1, 2].

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- This study used the computer software IBM ILOG CPLEX to solve the linear optimization. All of cycle time, total purchasing cost and selected function carrier variants are exported in the tables of Microsoft Access. Based on these results, the designer can easily choose the suitable solution.

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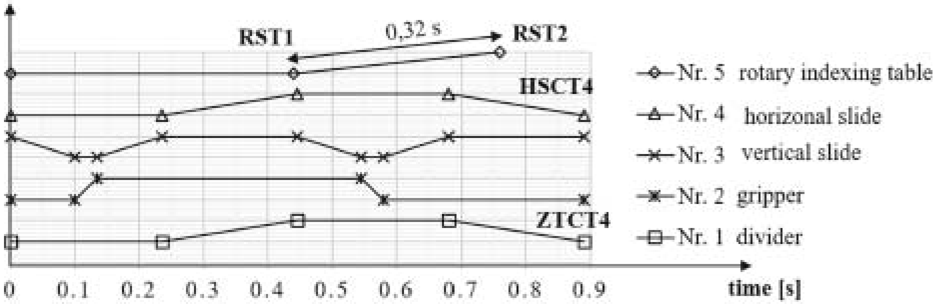
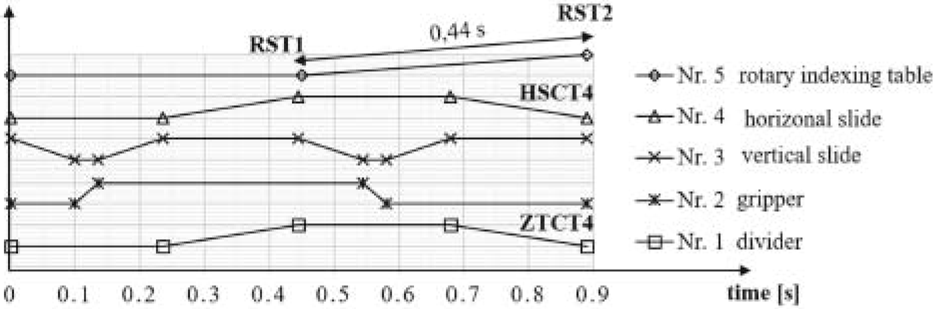


Optimal results of stage 1 in station 1



Optimal results of stage 1 in station 1

Fig. 8. Path-time diagram of station 1

4 Conclusions

The most important parameters of an assembly line are capacity and assembly cost. To reduce the assembly cost and increase the quality of machine, the designer should use the standard components. A large amount of function carrier variants can be chosen. It makes the designer difficult decide, which variants are better. For each solution, he must calculate the cycle time, total purchasing cost. This manual method spends a lot of time and cannot find the best solution. This study has shown the new method to optimize the cycle time and total purchasing cost by selecting the suitable variants from a given database. The main contents of this new method can be described as follows:

- The path-step diagrams of all station of a machine and assembly line must be established. These diagrams will determine the constraints of linear optimization.
- Based on the function carriers, the function carrier variants are listed and added to the tables of Microsoft Access.
- The standard form of linear optimization contains two stages. The first stage minimizes the cycle time of an assembly line. The second stage minimizes the total purchasing cost. The constraints of linear optimization are execution times of function carrier variants and path-step diagrams. To find out the other minimal cycle time and total purchasing cost, the constraint of total cost is defined in the stage 1.

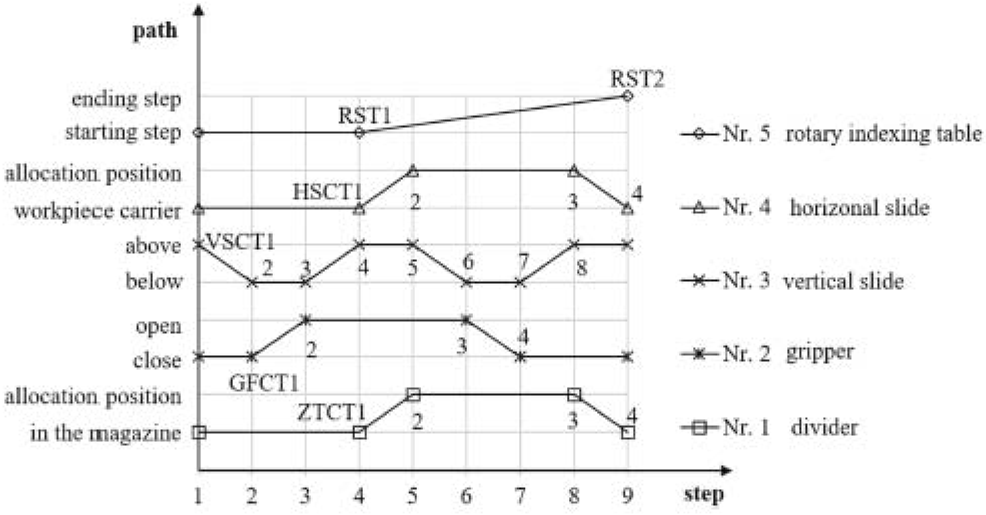


Fig. 7. Path-step diagram of station 1

where:

ZTCT1 to ZTCT4—change points of the divider No. 1
GFCT1 to GFCT4—change points of the gripper No. 2
VSCT1 to VSCT8—change points of the vertical slide No. 3
HSCT1 to HSCT4—change points of the horizonal slide No. 4
RST1, RST2—change points of the rotary indexing table No. 5

The results after stage 1 and 2 in Fig. 8 represent only the list of selected FCV. To control the points of time of each function carrier in the path-step diagram, the selected FCV, points of time, and costs are written to the other tables in database 2. Based on the points of time of the selected FCV, the time-step diagrams will be created. The differences between the selected variants in stage 1 and 2 are the moving times and purchasing costs. These differences are shown by the path-time diagram in Fig. 16, example for station 1.

The cycle time of station 1 was determined by the end times of the rotary indexing table No. 5, horizontal slide No. 4 and divider No. 1. In stage 1, these times are:

$$t^1_{\mathbf{RST},2} = 0{,}76\ \mathrm{s}, t^1_{\mathbf{HSCT},4} = 0{,}89\ \mathrm{s}, \quad \text{and} \quad t^1_{\mathbf{ZTCT},4} = 0{,}89\ \mathrm{s}$$

In stage 2, the other variants of the rotary indexing table with the bigger step times and lower costs is selected. The step time of the rotary indexing table has a value of 0.44 s instead of a value of 0.32 s. The end time of the rotary indexing table is $t^1_{\mathbf{RST},2} = 0{,}89$ s and does not exceed the cycle time $T^* = 0{,}89$ s.

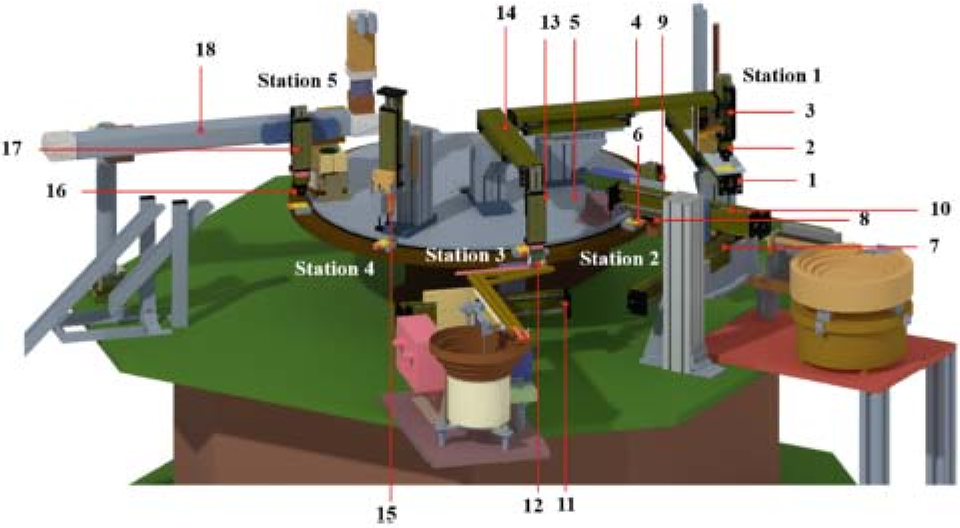
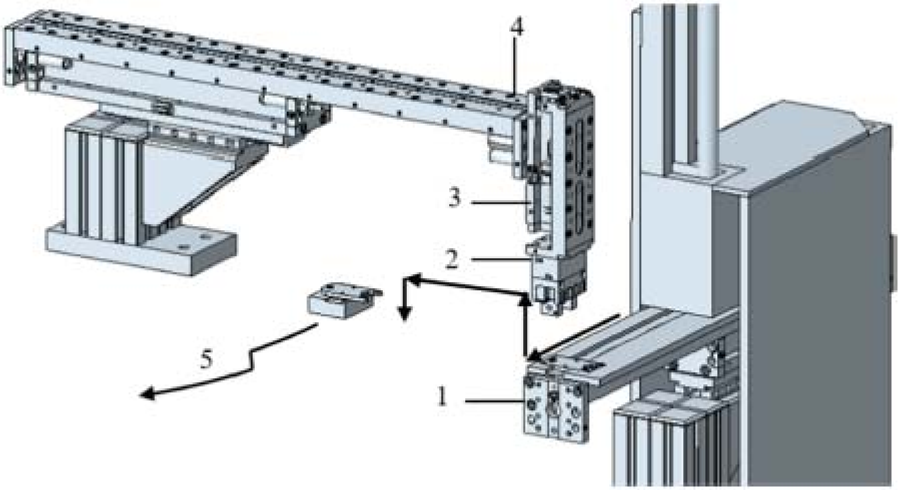


Fig. 5. Automatic rotary indexing machine



1- divider; 2- gripper; 3- vertical slide; 4- horizontal slide; 5- rotary indexing table

Fig. 6. Construction of station 1

Figure 6 shows the function carriers of station 1 and their working principles. A Chip holder is separated and handed over to the chip holder feeder. A transfer of the chip holder to the workpiece carriers on the rotary indexing table is generated by a pick & place module, consisting of a horizontal and a vertical axis.

In this example, the automatic rotary indexing machine contains five stations, so it requires to create five path-step diagrams. The cycle begins with the transfer of a chip holder in the gripper to the workpiece holder on the rotary indexing table. The path-step diagram of station 1 consists of nine steps and is described in Fig. 7.

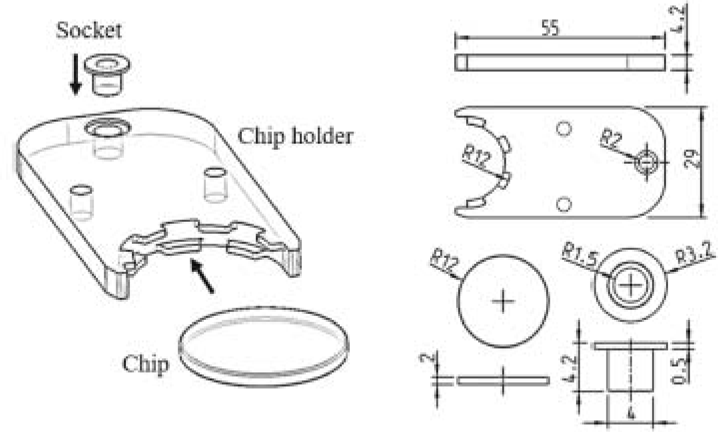


Fig. 4. Shapes and dimensions of socket, chip and chip holder

To assemble a chip, socket in chip holder, a handling process will be arranged in five stations:

- Station 1: Handover a chip holder
- Station 2: Insert a chip into chip holder
- Station 3: Insert a socket into chip holder
- Station 4: Attendant test a chip in chip holder
- Station 5: Ejection a chip holder

The new method for choosing standard components subject to minimal cycle time and minimal sum of purchasing cost can be applied in the different assembly and handling machines. In this paper, the new method is used in finding the best function carrier variants (handling module) of an automatic rotary indexing machine. This machine contains five stations (see Fig. 5). To optimize the cycle and purchase cost of components, it is necessary to point out the structure of each station, component as well as the work cycle. This example will present the configuration of station 1 as well as the path-step-diagrams of station 1 to station 5. The remaining stations are conducted similarly.

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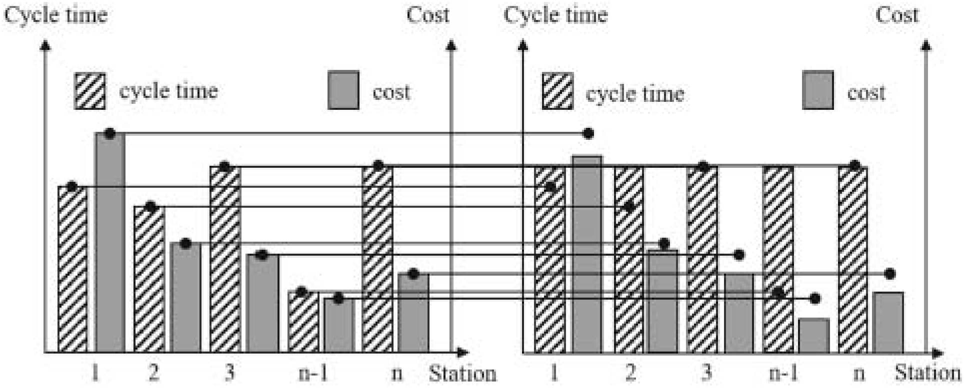


Step 1: minimum cycle time **Sep 2: minimum total purchasing cost**

Fig. 3. Difference between stage 1 and stage 2

It is essential in stage 2 to integrate total purchasing cost and the cycle time T into one optimization model. To optimize the total purchasing cost, the total cost of all selected FCV must be minimized. The purchasing cost of an FCV ν of the function carrier κ is called c_ν. Thus, the objective function of stage 2 is defined:

$$\min C_{\mathbf{SUM}} \Leftrightarrow \min \sum\nolimits_{\sigma \in \mathbb{S}} \sum\nolimits_{\kappa \in \mathbb{F}_\sigma} \sum\nolimits_{\nu \in \Gamma_\kappa} c_\nu \cdot \lambda^{\sigma}_{\kappa,\nu} \tag{11}$$

Cycle Time and Total Cost of Diagram

After solving the optimization problem in stage 1 and 2, only one solution is found. The FCV according to minimal cycle time and total purchasing cost are issued. The minimum cycle time is often not a primary goal to select an assembly machine. A designer wants to know, how much a machine costs with a given cycle time or how long the cycle time takes with a given total purchasing cost.

By manually changing the FCV in a database, the different values of the cycle time T and total cost $C_{\mathbf{SUM}}$ can be determined. However, it requires different tests and is not suitable for such an assembly system with numerous FCV. To solve this problem, the given total cost $C^*_{\mathbf{SUM}}$ will be defined in stage 1.

$$\sum\nolimits_{\sigma \in \mathbb{S}} \sum\nolimits_{\kappa \in \mathbb{F}_\sigma} \sum\nolimits_{\nu \in \Gamma_\kappa} c_\nu \cdot \lambda^{\sigma}_{\kappa,\nu} \leq C^*_{\mathbf{SUM}} \tag{12}$$

3 Application Example

An example for assembly product consists of three individual parts: a socket, a chip and a chip holder. Since both the chip and the socket are inserted into the chip holder, the chip holder is a base part. The shape and dimensions of the individual parts are shown from Fig. 4.

For a function carrier κ, only one FCV v is selected. Therefore, the sum of the values of binary variables is written:

$$\sum\nolimits_{v\in\Gamma_\kappa}\lambda^{\sigma}_{\kappa,v}=1,\forall\sigma\in\mathbb{S},\kappa\in\mathbb{F}_\sigma \tag{8}$$

where:

Γ_κ - Set of all FCV of the function carrier
$\kappa\in\cup_{\sigma\in\mathbb{S}}\mathbb{F}_\sigma$

Thus, the variable $t^{\sigma}_{\kappa,p}$ is redefined:

$$t^{\sigma}_{\kappa,p}=\sum\nolimits_{v\in\Gamma_\kappa}\tau^{p}_{v}\cdot\lambda^{\sigma}_{\kappa,v},\forall\sigma\in\mathbb{S},\kappa\in\mathbb{F}_\sigma,p\in\mathbb{P}^{\sigma}_{\kappa} \tag{9}$$

where:

$\mathbb{P}^{\sigma}_{\kappa}$ - Set of all executions/processes of the function carrier κ of the station σ. It should be noted that $\forall p\in\mathbb{P}^{\sigma}_{\kappa}:\{p_{\mathbf{START}},p_{\mathbf{END}}\}\subset\Delta^{\sigma}_{\kappa}$.
τ^{p}_{v} - Catalogue parameter represents the nominal execution time of the execution p of the FCV v of the function carrier $\kappa\in\mathbb{F}_\sigma$ in the station σ.

From the Eq. (11), the secondary condition (8) is rewritten:

$$t^{\sigma}_{\kappa,p_{\mathbf{END}}}-t^{\sigma}_{\kappa,p_{\mathbf{START}}}\geq\sum\nolimits_{v\in\Gamma_\kappa}\tau^{p}_{v}\cdot\lambda^{\sigma}_{\kappa,v},\forall\sigma\in\mathbb{S},\kappa\in\mathbb{F}_\sigma,p\in\mathbb{P}^{\sigma}_{\kappa} \tag{10}$$

Stage 2: minimum total purchasing cost according to the condition of cycle time

Stage 1 minimizes the cycle times of all stations. This means, that only the FCV with the smallest execution times from all FCL are selected. Therefore, all stations contain the FCV with the shortest execution times. There are usually different cycle times between these stations. The stations, which have cycle times less than the cycle time of the system $T=T_{max}$, can choose another FCV, can select FCV to have a longer execution times and cheaper purchasing costs. For this reason, the optimization problem will be run in stage 2. For the second stage, the cheaper FCV than FCV in stage 1 are searched, so that the new cycle times of the stations do not exceed the cycle time T. The different results between the first and second step are shown in Fig. 3.

objective function min T
under the constraints

$$\begin{array}{ll} T \geq T_\sigma, & \forall \sigma \in \mathbb{S} \\ T_\sigma \geq t^\sigma_{\kappa,\delta}, \forall \sigma \in \mathbb{S}, \kappa \in \mathbb{F}_\sigma, \delta \in \Delta^\sigma_\kappa & \end{array} \tag{4}$$

To shrink the many constraints above, the end times of the cycles of each station must be determined. In addition, the times of all function carriers in all stations must also be defined. These times are determined by the following conditions:

- Relationships between the times of the different function carriers inside a station and outside other stations:
  In the path-step-diagram, there is one or more changes of operations in a step. To calculate the points of time, the relationships between these changes must be considered. For example, in a step i (path-step-diagram) of a station σ, a function carrier κ ends a movement at the point of time $t^\sigma_{\kappa,\delta}$, and a function carrier $\tilde{\kappa}$ begins a movement at the point of time $t^\sigma_{\tilde{\kappa},\tilde{\delta}}$. Thus, such relationships must be represented by the following constraint. To determine a start-time movement of a function carrier in step 1 (cycle start), its time is assigned 0.

$$t^\sigma_{\tilde{\kappa},\tilde{\delta}} \geq t^\sigma_{\kappa,\delta} \tag{5}$$

- Relationships between the start and end times of a function carrier:
  For an operation p (for example, opening or closing of a gripper) of a function carrier κ of a station σ, there are a start time $t^\sigma_{\kappa,p\mathrm{START}}$ as well as an end time $t^\sigma_{\kappa,p\mathrm{END}}$, its difference represents the actual operating time of the operation p. Therefore, the following constraint must be defined:

$$t^\sigma_{\kappa,p\mathrm{END}} - t^\sigma_{\kappa,p\mathrm{START}} \geq t^\sigma_{\kappa,p} \tag{6}$$

  where: the positive variable $t^\sigma_{\kappa,p}$ on the right side represents the minimum actual operating time of the execution p and depends on the *function carrier variants (FCVs)*, which is selected for the function carrier κ.

In most cases, the right side of the constraint (8) must be considered not only for a single FCV, but also for the FCL. Therefore, a binary variable $\lambda^\sigma_{\kappa,v}$ is introduced for an FCV v of the FCL. The value of the binary variable $\lambda^\sigma_{\kappa,v}$ shows, whether an FCV v is selected in the list of a function carrier κ.

$$\lambda^\sigma_{\kappa,v} = \begin{cases} 1, & \text{chosen} \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

2.2 Establish the Optimization Problem by Mathematical Formulas

The optimization problem will be described by following standard form:

Stage 1: minimization of cycle time

In this section, the optimal cycle time T of the entire assembly system is assigned by the biggest cycle time T_{max} of all stations, or in other word, the cycle time of the assembly system T is determined by the slowest station.

$$T = \max_{\sigma \in \mathbb{S}} T_{\sigma} \tag{1}$$

where:

$\mathbb{S}$ - Set of all stations of the entire assembly system
T_{σ} - Cycle time of a station $\sigma \in \mathbb{S}$

The cycle time of the station σ is defined by all points of time of the function carriers of the path-step diagram:

$$T_{\sigma} = \max_{\substack{\kappa \in \mathbb{F}_{\sigma} \\ \delta \in \varDelta_{k}^{\sigma}}} t_{\kappa,\delta}^{\sigma}, \forall \sigma \in \mathbb{S} \tag{2}$$

where:

$\mathbb{F}_{\sigma}$ - Set of all function carries of the station $\sigma \in \mathbb{S}$
Δ_{κ}^{σ} - Set of points of time in the path-step diagram of the function carrier $\kappa \in \mathbb{F}_{\sigma}$ in the station σ
$t_{\kappa,\delta}^{\sigma}$ - Points of time according to a change of operation $\delta \in \varDelta_{\kappa}^{\sigma}$ of a function carrier κ in the station σ

Therefore, the minimization of the cycle time T applies to a min_max optimization problem. That means, the objective function is to minimize the maximum cycle times of all stations:

$$\min T \Leftrightarrow \min\left(\max_{\sigma \in \mathbb{S}} T_{\sigma}\right) \Leftrightarrow \min\left(\max_{\substack{\sigma \in \mathbb{S} \\ \kappa \in \mathbb{F}_{\sigma} \\ \delta \in \Delta_{\kappa}^{\sigma}}} t_{\kappa,\delta}^{\sigma}\right) \tag{3}$$

Currently, the objective function () has non-linearity, but can easily be reformulated and linearized by a series of constraints:

operation, e.g. switching a rotary indexing table, starting or stopping a slide unit, is referred to a step. A cycle begins with step 1 and ends with step n (see Fig. 1). After the last step n has completed, a new cycle starts. With a focus on minimizing cycle time, a diagram should be set up so that carrier functions have the least waiting time as possible.

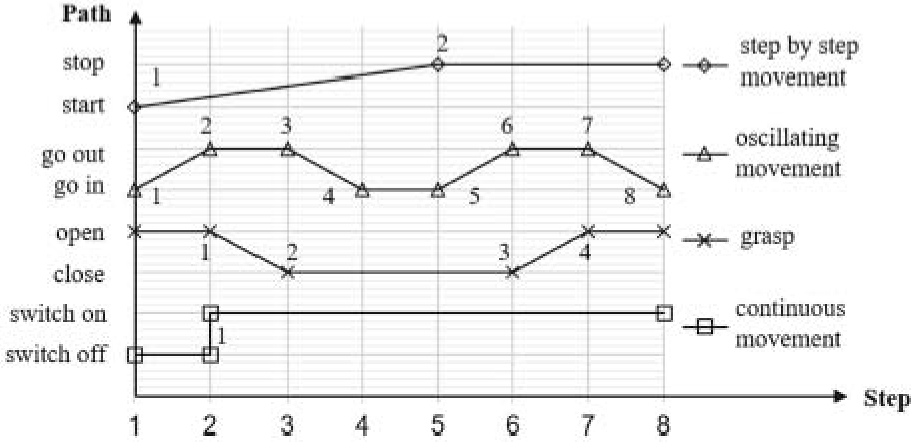
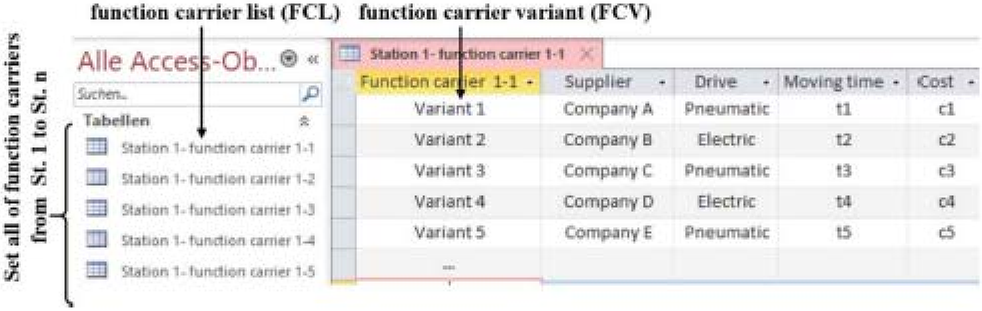


Fig. 1. Path-step-diagram of a station

As a means to define the time variables of the function carriers and the cycle time of a station, the change of operation is labelled in the path-step diagrams. For example, eight changes from 1 to 8 are defined for the oscillating movement. Thus, the events of this function carrier differ from other function carriers.

The optimization program selects the function carrier variants (FCV) from the function carrier list (FCL) according to the defined restrictions. Therefore, the FCL serve as the input parameters of the optimization problem. The execution time and purchasing cost of an FCV are the criteria for selection. Thus, the times, e.g. test or measurement time, movement time or response time of FCV as well as the purchasing cost, must be given in the databases (see Fig. 2).



Function carrier 1-1	Supplier	Drive	Moving time	Cost
Variant 1	Company A	Pneumatic	t1	c1
Variant 2	Company B	Electric	t2	c2
Variant 3	Company C	Pneumatic	t3	c3
Variant 4	Company D	Electric	t4	c4
Variant 5	Company E	Pneumatic	t5	c5
...				

Fig. 2. Structure of database of an assembly system in MS access

To perform the assembly and handling, function carriers are often used that implement assembly and handling task. A strong trend in designing machine is the use of standardized component units to reduce design time of complexity assembly lines [3, 4]. With a focus on selecting suitable components, criteria of function carriers must be defined, such as types, capacity, price, effectiveness and service [5]. The priority for a desired system is not only the shortest cycle times, but also an optimum price/performance ratio [6]. Minimizing the cycle time T is an important step in the-planning and design of an assembly system. By minimizing the cycle time, different target values can be achieved [7].

The assembly and handling operations are assigned to the various stations. Due to the different assembled products with the different assembly and handling operations, there are different cycle times between the stations [8]. To compare the cycle times of individual stations, the cycle time diagram should be created. A cycle time diagram shows the station with the maximum cycle time T_{max}, which is the so-called bottleneck station and reduces the efficient utilization in the assembly line. This assembly and handling processes in the stations with shorter cycle times than T_{max} must wait for the bottleneck station [9]. The following methods can be used to reduce the different cycle times and eliminate the bottleneck station. To balance the cycle times between the stations in assembly line, the assembly and handling operations are renewed to allocate to the different stations [7].

1.2 Removal of the Bottleneck Station

To select elements from sets of function carrier variants according to the objective function of the cycle time and purchasing cost, nowadays there is no efficient method. Many companies in the Germany, designing assembly machines such as SIM Automation GmbH, USK GmbH etc., manually select these elements from the supplier, and then calculate the raw cycle time and total purchasing cost. If a machine has n function carriers, each function carriers contains m variants, there are n^m different options for selecting the components of the assembly machine. Therefore, if the selecting process is manual, the number of tests will be extremely large, and it will not be able to find an optimal solution. The goal of this research is to build an algorithm to find an optimal solution according to the given conditions in term of minimal cycle time and total purchasing cost [10]. An assembly system comprises different stations, a station consists of the different function carriers.

2 Methods of Study

2.1 Describe the Operations of Assembly and Handling Function Carriers

The operations of all function carriers are determined based on the assembly and handling task. These individual operations of a function carrier in the station decide a cycle time of a station. To determine the cycle time of the station, all operations must be indicated in path-step diagrams and divided into different steps. A change of