The Concept of the PlantTwin discrete manufacturing simulation tool

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1. Introduction

1.1. Scope

This document defines the concept of the PlantTwin discrete manufacturing simulation tool. It describes:

- features of the simulated subject area;
- basic functionalities of the PlantTwin tool;
- restrictions and assumptions applied to the use of PlantTwin.

1.2. Purpose of the tool

PlantTwin is designed to support decision-making in the strategic and medium-term scheduling of production in workshops, plants and groups of enterprises. PlantTwin can be used to address the following problems:

- evaluating adequacy of production capacities of a workshop, enterprise or group of enterprises for production plan delivery;
- justification of investments in the modernization of existing and creation of new production capacities;
- production plan feasibility check through simulation modeling;
- generation of a supported production plan;
- scenario analysis of cooperation in cooperation between enterprises of a holding company or affiliate.

1.3. Scope of the simulated object

The PlantTwin tool plans and simulates processes in the workshops of a production plant. It examines the production assets of an enterprise (Work Centers, storage facilities) and the flow of materials comprising products stored in storage facilities, processed and assembled in Work Centers and transferred by the transportation network of a company. The simulated system structure is described in more details in paragraph 2.1.

1.4. Simulation premises and assumptions

No.	Premise or assumption
1	Alternative production flows are not considered: each product assembly undergoes a uniquely defined sequence of operations in order to be produced.
2	Transportation constraints such as crane operations and availability of transfer cars are not simulated. It is assumed that there are always sufficient means of transportation to perform all the required operations.
3	The PlantTwin does not calculate the number of operatives required.
4	Full discreteness of a simulated material flow is assumed: none of products can be divided into parts in the simulation process. Thus, all the quantities are integer nonnegative values.
5	PlantTwin does not consider the work schedules of warehouses and other facilities where assemblies are stored. It is assumed that assemblies stored in a warehouse are available for use at any time.

2. Simulated objects and entities

2.1. General description of the simulated system

2.1.1. Structure and composition of the simulated system

The simulated system is an enterprise that runs the discrete manufacturing of assemblies using a predefined technology in accordance with the production plan.

The structure of the simulated system is illustrated in Fig. 1 below.
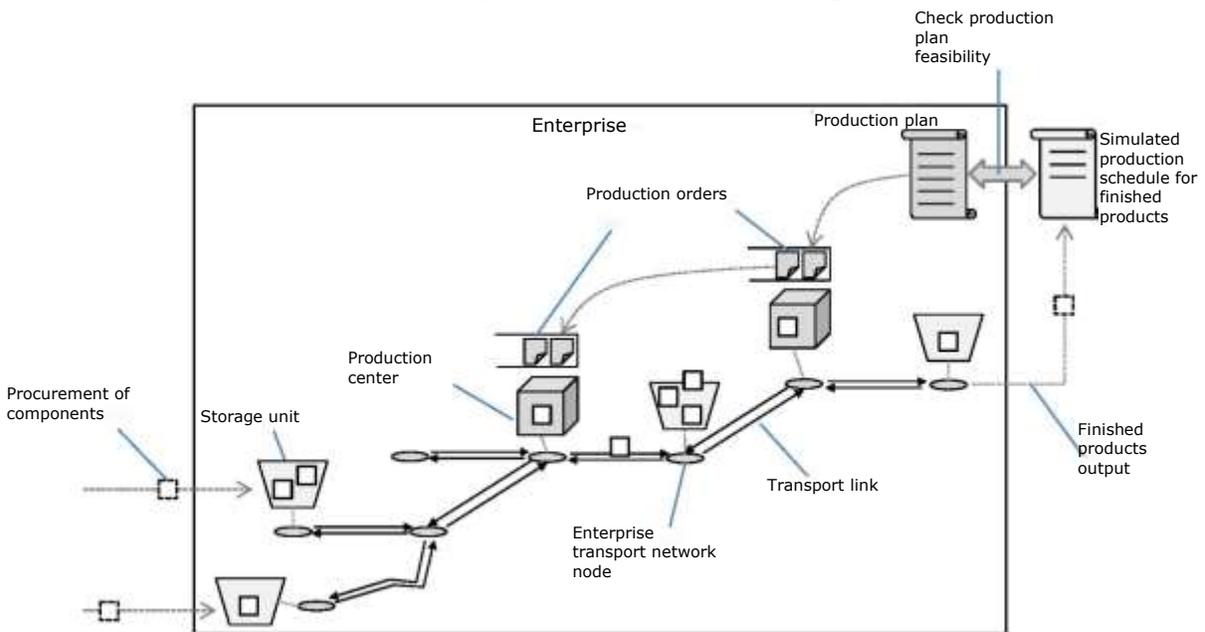
Fig. 1. Schematic diagram of the simulated system structure

The simulated subject area includes the following basic objects and entities:

- Material flow is a set of all assemblies manufactured at the enterprise and used in production as components;
- Production capacities:
  o Work Centers (WC),
  o Types of Work Centers,
  o Application of WC work schedules (accounting for shiftwork and non-working days),
  o Scheduled periods of WC unavailability,
  o Age-related repairs,
  o WC failures,
  o Storage facilities,
  o External contractors;

- Basic production data:
    - Operations,
    - Productivity of WCs,
    - Productivity of external contractors,
    - Initial inventory records,
    - Replenishment records;
- Production plan that defines the target production schedule for finished products;
- Transportation network of the enterprise:
    - Transportation network nodes,
    - Transportation links.

2.1.2. Functioning of the simulated system

PlantTwin logic is divided into two blocks: a scheduler and simulation module. PlantTwin works in two successive steps:

1. Scheduling the work of Work Centers performed by the scheduler.
2. Simulation of work performed in the Work Centers by the simulation module on the basis of the schedule generated by the scheduler.

The scheduler is intended to schedule the work of WCs that execute operations with assemblies to achieve production delivery targets. The scheduler takes into account the following:

- Maximum duration of operations,
- Work schedules of WCs,
- Scheduled periods of WC unavailability,
- Age-related repairs.

The simulation model reproduces in detail the work of Work Centers. The schedule generated by the scheduler serves as an input for the simulation module. The timeliness of schedule fulfillment depends on the following factors considered in the simulation module and not accounted for by the scheduler:

- Probabilistic distribution of the duration of operations (triangular distribution),
- Delays in the delivery of purchased items,
- Overfilling of storage facilities that results in the inability to timely transfer parts and components between the Work Centers in a timely manner.

2.2.   Material flow

Material flow is a set of all assemblies manufactured at the enterprise and used in the production as components.

2.2.1.   Product

A product is a generic term used to describe a unit in the material flow that has a physical form, for example, "Bolt M6x14".

2.2.2.   Assembly

An assembly is a generic term used to describe a unit in the material flow that contains information about its physical realization and manufacturing process. For example, the product "Bolt M6x14" can be manufactured using various combinations of operations: milling on a milling machine or use of a die head on a fitter bench. In this case, one product has two corresponding assemblies each having a unique identifier in PlantTwin, for example, A-1 and A-2.

2.2.3.   Assemblies tree

To represent the interrelation between assemblies in the process of final product manufacturing, the concept "tree of product items" concept is used. Fig. 2 illustrates an example of a assemblies tree.

Product name	Product ID	Quantity	Product item ID
Izd_0.1	Izd_0.1	1	A-1
Izd_0.1.1	Izd_0.1.1	1	A-2
Izd_0.1.1.1	Izd_0.1.1.1	1	A-3
Izd_0.1.1.2	Izd_0.1.1.2	1	A-12
Izd_0.1.1.3	Izd_0.1.1.3	1	A-22
Izd_0.1.1.3.1	Izd_0.1.1.3.1	3	A-23
Izd_0.1.1.3.2	Izd_0.1.1.3.2	1	A-26
Izd_0.1.1.3.3	Izd_0.1.1.3.3	1	A-31
Izd_0.1.1.3.4	Izd_0.1.1.3.4	1	A-34
Izd_0.1.1.3.5	Izd_0.1.1.3.5	3	A-40
Izd_0.1.1.3.5.1	Izd_0.1.1.3.5.1	1	A-41
Izd_0.1.1.3.5.2	Izd_0.1.1.3.5.2	1	A-42
Izd_0.1.2	Izd_0.1.2	1	A-43
Izd_0.1.3	Izd_0.1.3	1	A-44

Fig. 2. Assemblies tree

2.2.4. Logistic categories

Logistic categories are used to calculate the time needed to transfer product items. Examples of logistic categories include "Weight from 1 to 10 kg", "Volume up to 0.1 m³", etc. One or more logistic categories can be defined for each product.

2.2.5. Capacity types

For capacity simulation purposes, capacity types are used. Examples of capacity types are "Weight", "Width", etc.

2.2.6. Capacity utilization factor

A capacity utilization factor can be defined for products to indicate how many units of capacity are required for one item of the product. The capacity utilization factor of the product, its "size", is indicated in terms of capacity types. For example, the capacity utilization factor of product item A in terms of "Weight, kg" is 10 kg, while in terms of "Length, m" it is 0.8 meters.

2.3. Production capacities

2.3.1. Work Centers (WC)

A Work Center is an object where operations of processing and assembling of assemblies are carried out. A Work Center can execute a fixed set of operations.

2.3.2. Types of Work Centers

WC type is an entity used to group similar WCs when specifying data and displaying statistics. The production rate and the set of available operations are defined in terms of WC types.

2.3.3. WC work schedules

Work Centers operate in accordance with defined schedules. The schedule determines periods of scheduled availability and unavailability of WCs. The WC work schedule is defined as a repeating set of WC availability periods in terms of days of the week. An example of a two-shift work schedule for a five-day working week is shown in Fig. 3.

Schedule	ShiftName	BeginWeekDay	BeginTime	EndWeekDay	EndTime
2 shifts 5 days	1	MON	8:00	MON	12:00
2 shifts 5 days	1	MON	13:00	MON	13:00
2 shifts 5 days	2	MON	8:00	MON	22:00
2 shifts 5 days	2	MON	23:00	TUE	3:00
…					
2 shifts 5 days	1	FRI	8:00	FRI	12:00
2 shifts 5 days	1	FRI	13:00	FRI	13:00
2 shifts 5 days	2	FRI	8:00	FRI	22:00
2 shifts 5 days	2	FRI	23:00	SAT	3:00

Fig. 3. Example of defined two-shift work schedule for five-day working week

Sets of non-working days (holidays) are defined separately as sets of dates when the WC is unavailable regardless of the schedule.

At any one time WC can only work in accordance with one schedule and one set of non-working days.

2.3.4. Scheduled periods of WC unavailability

A scheduled repair is a planned shutdown of the Work Center to carry out scheduled minor repairs, overhauls or other repair activities. Starting up or shutting down the WC is also determined by the scheduled periods of unavailability.

2.3.5. Age-related repairs

An age-related repair is a repair carried out after the WC has reached the specified number of operating hours of its engine/actuation mechanism.

2.3.6. WC failures

To simulate emergency outages of the WC, failures, i.e. unscheduled shutdowns of the WC, are used. The failure occurrence time can be set based on the calendar time, the operating time of the WC (operations, set-ups and cleaning) or the execution time of operations.

2.3.7. Storage facilities

A storage facility is an object where assemblies are stored during the time that they are not processed at the Work Center and are not transported over the enterprise site.

Storage facility capacity is defined in terms of capacity types. Only one type of capacity is specified for each storage facility and constitutes its limiting factor. For example, the storage facility can be large in size, but have restrictions on the weight of the assemblies contained in it. In this case the capacity type "Weight" and the capacity value in units of weight will be defined for the storage facility.

2.3.8. External contractors

An external contractor is an entity where, just as at a Work Center, processing and assembling operations can be performed.

2.4. Basic production data

2.4.1. Operations

A production operation is part of a technological process performed at one WC comprising a series of actions with the product item or group of assemblies processed together. Each operation can be performed at the WC of one or several types. The duration of the operation may vary depending on the type of WC.

2.4.2. Productivity

The WC productivity record determines the duration of an operation depending on type of WC. When changing operations at the WC, additional actions may be required to replace tooling or to perform clean, etc. In order to simulate the time required for such additional actions, the simulation tool uses set-ups and cleaning. The set-up of a WC in the simulation is a specified time delay before the operation, provided that prior to this another operation or WC repair has been performed. Cleaning is a delay in the execution of final actions after the operation is completed, provided that another operation or repair of the WC is performed after this delay.

2.4.3. Productivity of external contractors

If an operation is executed by third parties without using the production capacities of the simulated enterprise, the productivity of the external contractor is specified for this operation, i.e. the duration of the operation executed by the external contractor.

2.4.4. Initial inventory

The initial inventory comprises assemblies processed in varying degrees and available in storage facilities at the start of the simulation.

2.4.5. Purchased product

Some products used in the manufacture of the finished product may be purchased. These products require the definition of inventory maintenance parameters: frequency of orders, delivery time, minimum batch size, order ratio and buffer inventory.

2.5. Production structure

The system allows the structure of an enterprise or group of enterprises to be defined. The production structure is hierarchical and consists of organizational units. Each organizational unit may contain one or more nested organizational units. The hierarchical structure is tree-like, i.e. each organizational unit can only belong to one parent organizational unit. The root unit has no parent unit. The production structure has only one root element.

Organizational units are used to group WCs. WCs can be located only at the lower (terminal) level of the hierarchy.

2.6. Production plan

The production plan defines the target production schedule of finished products. It specifies how many assemblies of each type must be manufactured, and without what timeframe.

2.7. Transportation network

2.7.1. Transportation network nodes

The node of a transportation network is a point in the two-dimensional layout of the enterprise. Each WC and storage facility is linked to only one node. However, one node can have several objects (Work Centers or storage facilities) linked to it.

2.7.2. Transportation links

A transportation link connects two nodes of a transportation network. All transportation links are bidirectional. All movements along transportation links are performed in a straight line from one node to another.

3. Simulated processes and algorithms

3.1. Scheduling algorithm

3.1.1. General concept of the scheduling algorithm

Scheduling of production delivery targets consists in determining start and end times for all necessary operations at Work Centers as well as times to purchase components and quantities of components to be purchased.

Work at the WC is scheduled by arranging batches on a time axis. A slot is a continuous period of time during which the WC remains in one state. Batches can be of the following types:

- Unscheduled period (e.g. lunch time or weekend);
- Scheduled repair;
- Work:
    - Operation execution,
    - Set-up,
    - Cleaning.

An example of the time axis of a WC with batches arranged on it is shown in Fig. 4.

Fig. 4. Example of the time axis of a WC with batches

The purchase of components is scheduled on the basis of the schedule of needs on the assumption that suppliers have no restrictions on quantity of delivered goods.

In the course of scheduling, batches are arranged in reverse order, starting with batches of final operations necessary for the production of finished products in accordance with the production plan. For example, if the production of product item A requires, first, to produce assemblies B and C, the production of product item A is scheduled first, then the production of assemblies B and C by the date of commencement of work on product item A. This approach removes the uncertainty of slot arrangement time that would otherwise arise with "forward" scheduling, i.e. from the deepest elements of the assemblies tree (Fig. 5). In reverse scheduling, the uncertainty is eliminated by assuming that the product item can be produced by a given date. Thus, in the course of scheduling the time axes of WCs are filled with batches from right to left, i.e. from later operations to earlier ones.
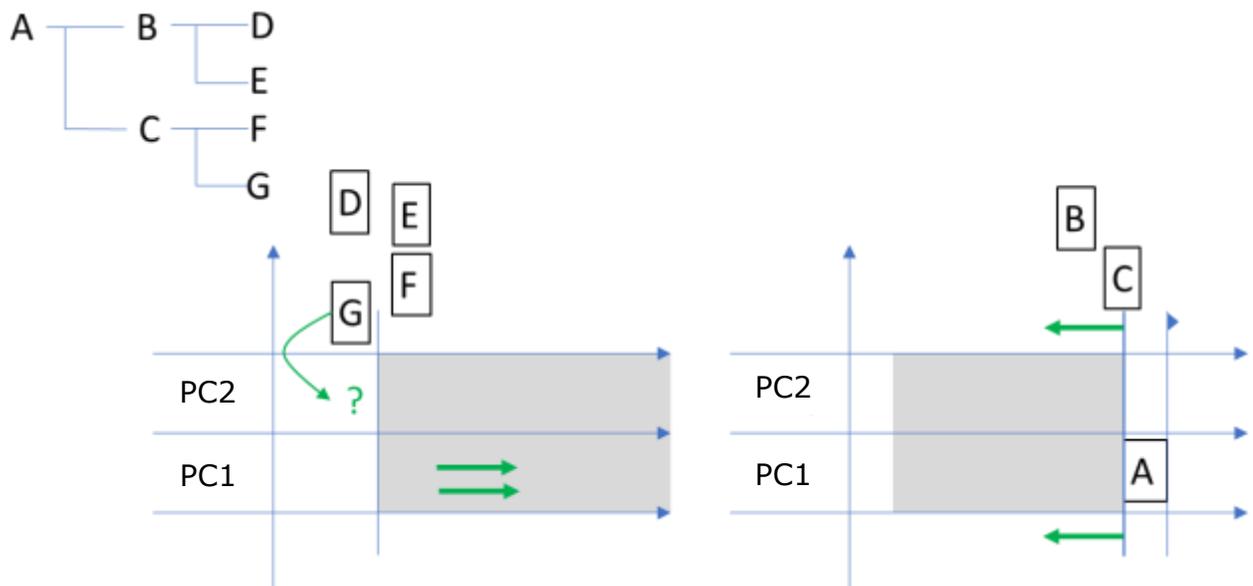
Fig. 5. "Direct" and "reverse" scheduling

Scheduling is carried out step by step, batches scheduled at all previous steps are transferred to the input of each subsequent step. As a result of each step, one operation is always scheduled. However, the number of new batches can be equal to any value, in particular:

- 0 batches if the operation is to be executed by an external contractor;
- 1 slot – the most clear case – when 1 time period is enough to complete the operation, no set-up and unset-up is required;
- More than 1 slot – the duration of the operation is longer than the free gap of the WC. For example, a WC works for 8 hours a day, and the duration of an operation is 20 hours, then at least three batches should be scheduled to complete the operation. In addition, extra batches can be scheduled for set-up and unset-up.

A scheduling alternative is a combination of an operation, a WC or a contractor, through which this operation can be completed. For example, if operation X can be performed at WC1 and WC2, there can then be two scheduling alternatives: (X, WC1) and (X, WC2). At each scheduling step, all alternatives are generated, one of them is selected, and batches are arranged on the WC axes in accordance with the selected alternative. Scheduling ends when the set of alternatives is empty.

3.1.2. Description of the scheduling algorithm

During the execution of the scheduling algorithm, the following sequence of actions is performed:

1. Arrangement of batches for periods of unavailability and unscheduled periods for all Work Centers.
2. Generation of the initial set of alternatives based on the latest operations needed to deliver production target.
3. Repetition of actions 3.1-3.6 until the set of alternatives is empty:
   3.1. Select one alternative from the set;
   3.2. If selection of an alternative was unsuccessful, proceed with step 4;
   3.3. Remove all alternatives for the selected operation from the set;
   3.4. If the alternative implies execution at a WC, then:
       3.4.1. Add to the WC axis all the batches needed for the operation, otherwise,
       3.4.2. Schedule the execution of the operation by an external contractor;
   3.5. Add the need for purchased components at the start of the scheduled operation;
   3.6. Supplement the set of alternatives with new ones resulting from completion of the selected operation.
4. Calculate the procurement schedule for purchased components based on the schedule of needs and replenishment records.

Actions 1 and 2 are preliminary actions that are performed once at the beginning of the scheduling process. Actions 3.1–3.6 are actions in a scheduling step. Action 4 is the final action of the scheduling process. If, upon completion of the scheduling algorithm, all the necessary operations are scheduled, then the scheduling is considered successfully completed.

The work of the scheduling algorithm is determined by the rule of alternative selection applied in action 3.1. The rule of alternative selection used in a specific implementation of the algorithm is called a scheduling strategy.

3.1.2.1 Scheduling launch batches

Launch batches are scheduled on a step-by-step basis: steps that include scheduling of operations without restrictions on the minimum launch batch alternate with generating the schedule for production of batches of a given product item.

When scheduling batches, the following restrictions apply:

- A batch is scheduled as a continuous sequence of steps uninterrupted by the scheduling of other operations;
- All operations in a batch are completed at one WC;
- All the components required for production of assemblies of the batch must be produced or purchased by the execution time of the first operation of the batch;
- Each subsequent operation with assemblies of one batch shall only be executed after the previous operation with all assemblies of this batch is completed.

3.1.3. Scheduling strategies

Scheduling strategies are applied at the stage of selecting alternatives. When selecting each next alternative, the first alternative is selected from the list of all alternatives sorted successively by a set of criteria. Successive sorting means turn-based sorting of alternatives by an ordered list of criteria. Alternatives corresponding to the same value of the previous criterion are sorted by the following criterion, etc. The last criterion of all strategies is the sequence number of the alternative, which makes the scheduling reproducible. The list of criteria for sorting alternatives forms a scheduling strategy.

3.1.3.1 Scheduling strategy A

Scheduling strategy A is defined by the following set of criteria for sorting the alternatives:

1. Type of execution of operations (first, alternatives are scheduled that correspond to operations executed by external contractors followed by operations executed using in-house resources).
2. The alternative continues a started launch batch (alternatives that continue launch batches are assigned with higher priority).
3. The sequential number of a started launch batch (first, the alternatives are scheduled that correspond to the batches started earlier).
4. The alternative continues a process batch (alternatives that continue a process batch are assigned higher priority, then follow the alternatives that do not require grouping into process batches, finally, the alternatives starting new process batches follow).
5. The moment when the operation is completed (alternatives with the latest completion time are scheduled first).

6. Total time needed for a WC to complete the alternative, taking into account breaks, weekends, set-ups and cleaning (alternatives with minimum time are scheduled first).
7. Operation delay (alternatives with the least delay are scheduled first).
8. The number of alternative WCs where the operation can be executed (the alternatives with a large number of alternative WCs are scheduled first).
9. The number of operations as far as the root element of the production plan, i.e. the depth of operation nesting (alternatives corresponding to operations with the smallest nesting depth are scheduled first).
10. Scheduled completion time of the operation (alternatives corresponding to operations with a minimum scheduled completion time are scheduled first).
11. Sequential number of the alternative, which is necessary to ensure reproducibility of the scheduling.

3.1.3.2 Scheduling strategy B

Scheduling strategy B is defined by the following set of criteria for sorting the alternatives:

1. Type of execution of operations (first, alternatives are scheduled that correspond to operations executed by external contractors, then those that are executed using in-house resources).
2. The alternative continues a started launch batch (alternatives that continue launch batches are assigned with higher priority).
3. The sequential number of a started launch batch (first, the alternatives are scheduled that correspond to the batches started earlier).
4. Time when the operation is completed (alternatives with the latest completion time are scheduled first).
5. The alternative continues a process batch (alternatives that continue a process batch are assigned higher priority, then follow the alternatives that do not require grouping into process batches, finally, the alternatives starting new process batches follow).
6. Total time needed for a WC to complete the alternative, taking into account breaks, weekends, set-ups and cleaning (alternatives with minimum time are scheduled first).
7. The number of alternative WCs where the operation can be executed (the alternatives with a large number of alternative WCs are scheduled first).
8. The number of operations as far as the root element of the production plan, i.e. the depth of operation nesting (alternatives corresponding to operations with the smallest nesting depth are scheduled first).
9. Scheduled completion time of the operation (alternatives corresponding to operations with a minimum scheduled completion time are scheduled first).

10. Sequential number of the alternative, which is necessary to ensure reproducibility of the scheduling.

3.1.3.3 Scheduling strategy C

Scheduling strategy C is defined by the following set of criteria for sorting the alternatives:

1. The alternative continues a process batch (alternatives that continue a process batch are assigned higher priority, then follow the alternatives that do not require grouping into process batches, finally, the alternatives starting new process batches follow).
2. The alternative continues a started launch batch (alternatives that continue launch batches are assigned with higher priority).
3. The sequential number of a started launch batch (first, the alternatives are scheduled that correspond to the batches started earlier).
4. Sequential number of the alternative, which is necessary to ensure reproducibility of the scheduling.

3.1.4. Scheduling replenishment of purchased products

Replenishment of purchased components is scheduled after completion of all scheduling steps based on the need for purchased products. Replenishment is scheduled independently for each product.

Input for replenishment scheduling of a product is the schedule of product needs and the product's initial inventory. In addition, when scheduling replenishment needs, the replenishment parameters defined for each product in the input data are taken into account:

- buffer inventory level;
- delivery frequency delivery frequency;
- minimum order quantity;
- maximum frequency of orders;
- scheduled delivery time.

Replenishment is scheduled in accordance with the following algorithm:

1. Set the current scheduling time T to the start date of the simulation.
2. Set current inventory S to the initial inventory.
3. Use the schedule of needs to determine the time T1 when the decreasing inventory level S1 becomes less than the buffer inventory level SS. Note that S1 may have a negative value.
4. If time T1 > the end time of the simulation, end the algorithm run.
5. Calculate the net required size as follows: R = SS – S1.

6. Round up the value of R up using the minimum delivery frequency Q: R1 = roundup(R / Q) * Q
7. Calculate the quantity to purchase: PQ = max(MOQ, R1), where MOQ is the minimum order quantity.
8. Calculate the corrected order time: T2 = rounddown(T1 - LT, OF) * OF, where OF is the frequency of ordering and LT is the scheduled delivery time.
9. Add the (T2, PQ) pair to the procurement schedule, correct the schedule of the need.
10. Proceed with step 3.

As a result of the replenishment scheduling algorithm run for each required purchased product, a procurement schedule will be calculated consisting of records (T, PQ), where T is the time of placing the purchase order and PQ is the quantity of the product ordered.

3.1.5. Scheduling transportation of product items

The scheduler's logic of assemblies transportation within the enterprise is similar to the logic of assemblies transportation in the simulation model (see sub-point 3.2.6).

3.2. Simulated processes

3.2.1. Production according to a schedule

Assemblies are produced at WCs through the execution of operations. The production process comprises the following steps:

1. The simulation model uses the schedule and generates a sequence of operations for each WC according to the schedule.
2. In the simulation process, the execution of operations with a product item can be started earlier than the scheduled start date of the operation generated by the scheduler if the product item in the scenario is set to start earlier than the scheduled date. For example, if the scheduled start date of operation O-1 with the product item Izd-1 is March 12 at 8.00 am and the tree of assemblies has specified 3 days earlier start for Izd-1, then operation O-1 in the simulation will start on March 9 at 8.00 am.
3. The operation begins when the following two conditions are met:
   o The WC scheduled to execute this operation is available for work: the center is not shutdown for a break or repair and does not perform another operation.
   o All operations preceding the operation in question according to the technological process are completed and all components needed for the operation are ready.

4. If the WC is unavailable, the operation waits for it to be released to begin to execute the operation.

5. If previous operations have not been completed according to the technological process, the WC can start execution of the next operations in the queue but only if it can complete the started operation before the scheduled start date of the operation, which is waiting for its previous operations to be completed.

6. When performing operations with batches, the processed assemblies of one batch shall be stored in the output buffer of the WC until the batch is gathered, after which all the batches are fed into the input storage facility of the WC where the next operation will be executed.

3.2.2. Operation of the Work Centers

3.2.2.1 Operation of the Work Centers according to a time schedule

The Work Centers operate in accordance with defined time schedule. The time-schedule determines periods of scheduled availability and unavailability of WCs.

The following rules are used to determine the set of WC availability periods:

- Active periods of WC work may not be limited to one day;
- Active periods of WC work cannot exceed the week, i.e. they cannot contain the moment of time corresponding to 00:00 on Monday;
- Non-working days (holidays) cancel only those active periods that begin within a the non-working day (holiday) while the active periods that started earlier remain unchanged;
- Records of a time-schedule change apply only to active periods beginning no earlier than the recording date. It is also impossible to change the WC time-schedule during an active period.

If the end of an active period occurs during the period of operation execution, then the operation is suspended and resumed at the beginning of the next active period.

3.2.2.2 Scheduled periods of unavailability

A scheduled repair is a planned shutdown of the Work Center to carry out a scheduled minor repair, an overhaul or other repair activities, as well as to define a WC start-up or shut down. Scheduled periods of unavailability do not interrupt an operation but occur after completion of the operation.

To carry out scheduled repairs, only the time of active periods of the WC can be used.

3.2.2.3 Age-related repairs

The need for age-related repair arises when a certain number of operating hours of the WC is reached. When determining the number of operating hours of the WC, only the time during which the WC executed operations, set-ups and cleaning is taken into

account. Age-related repairs do not interrupt an operation but are performed after the operation is completed.

If the scheduled repair time occurs during an age-related repair period, the scheduled repair starts immediately after completion of the age-related repair.

To carry out an age-related repair only the time of active periods of the WC can be used.

3.2.2.4 Failures

A failure is an unscheduled (emergency) shutdown of the WC. Failures interrupt the execution of operations as well as the execution of scheduled repairs and age-related repairs.

The whole calendar time is used to eliminate failures, regardless of periods of WC activity.

3.2.3. Work of external contractors

The work of external contractors is simulated by a delay for the time of operation execution in accordance with the schedule that the contractor adheres to.

For each contractor, a work schedule is defined in the system. If the need arises to execute an operation by an external contractor, the operation begins at the time of the nearest working period of the contractor and is executed only in active periods of this contractor (similar to WC work). It is therefore possible to represent the work of external contractor as infinite resources capable of performing predefined operations in accordance with the schedule.

3.2.4. Storage of assemblies in storage facilities

Products are stored in storage facilities pending processing at the WC or moving to another storage facility. Assemblies that are finished products leave the system immediately after the end of production process without being stored in storage facilities. When storing assemblies in storage facilities, the following condition must be met at all times: the sum of capacity factors of the assemblies stored in the storage facility in terms of the specified type of storage facility should not exceed the storage facility capacity.

If the capacity of the storage facility is not specified, then an unlimited capacity is assumed and the storage facility can accommodate any number of assemblies with any capacity coefficient.

3.2.5.   Receipt of purchased products at the enterprise

The receipt of purchased products at the enterprise is simulated by a delay from the moment of ordering the products until they appear in the virtual storage facility with unlimited capacity.

The time of placing a purchase order is determined on the basis of the schedule generated by the scheduler (3.1.3.1).

The time of arrival of the ordered purchased product is simulated using the delivery time specified for the product in the input data and the probability deviation from the delivery time.

3.2.6.   Transportation of assemblies within the enterprise

Assemblies can be transported within the enterprise between any two different nodes of the transportation network of this enterprise. It is assumed that the transportation network of the enterprise forms a connected graph, that is, there is at least one route between any two nodes.

The itinerary of assemblies is defined as the geometrically shortest path through the transportation network of the enterprise. If there are several shortest paths, one of them is chosen randomly.

Travel time of products is calculated using organizational units, which include WCs and logistic categories of products.

For terminal nodes of the organizational structure, the travel time of movements between any two WCs of the same organizational unit, as well as travel time of movement from the unit entry point to a specific WC is defined.

For several organizational units that belong to the same parent organizational unit, transportation links are defined with the travel time specified for the movement between the corresponding organizational units.

Travel time for movement of products between WCs of different organizational units always consists of 3 components:

- Travel time to move inside the original organizational unit,
- Travel time to move between organizational units of one hierarchical level,
- Travel time to move inside the target organizational unit.
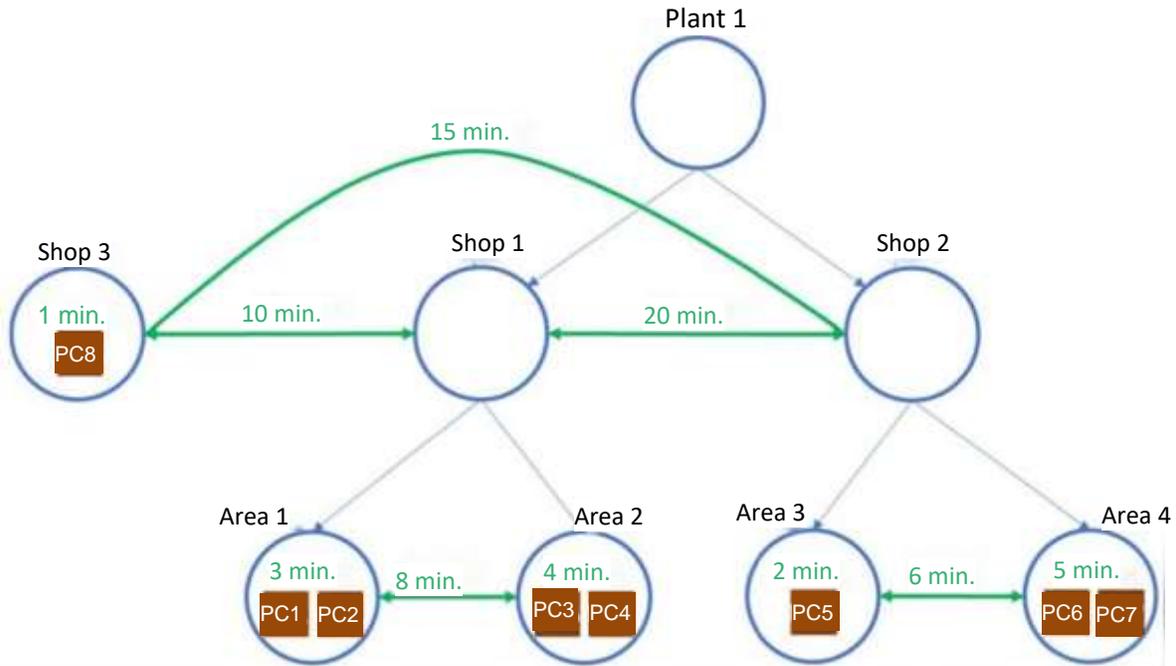
Fig. 6. Travel time to move assemblies

For the example of organizational structure shown in Fig. 6, travel times to move a product item between the WCs are as follows:

- travel time to move between WC1 and WC2 (inside area 1) is 3 min;
- travel time to move between WC1 and WC3 (between areas 1 and 2) is 3 + 8 + 4 min;
- travel time to move between WC1 and WC6 (between workshops 1 and 2) is 3 + 20 + 5 min;
- travel time to move between WC1 and WC8 (between workshops 1 and 3) is 3 + 10 + 1 min.

All travel times are defined for specific organizational units and logistic categories. When calculating a travel time, the maximum value for each of movement stages is used.

In the absence of a record of travel time to move a product, this time is taken equal to zero.

The movement is asymmetrical. This means that it is necessary to specify the movement from OE1 to OE2, and in the reverse direction, from OE2 to OE1, and these values can be different.

Logistic categories are not defined for purchased assemblies since their movements are not scheduled and simulated.

3.2.7. Production without scheduling

Assemblies are produced without scheduling at WCs through the execution of operations. The production process comprises the following steps:

1. Based on the maximum duration of operations, the sequence of operations is generated in the reverse order, starting with the last operations necessary for production of the finished products.
2. Based on the generated sequence of operations, scheduled delivery dates for purchased products are determined. All purchased products required by the same date are ordered in one batch.
3. Work Centers choose operations from all the operations for which components are available, according to the scheduled date of readiness: operations with AN earlier scheduled date of readiness are executed first.

In case of simulation without scheduling, storage and transportation of assemblies are not simulated. When the WC is ready to execute an operation, the product item of this operation appears at the WC immediately.

3.3. Scenario analysis

Scenario analysis allows simultaneous running of simulation of several scenarios and comparison of the results of their simulation in one window.

3.4. Monte Carlo analysis

The Monte Carlo analysis enables simultaneous running of several simulation iterations of the same scenario using different values of random variables and then comparison of the results in one window.

4. Output data

4.1. Visualization data of the scheduler and simulation model

The scheduler and simulation model contain a dynamic visualization that allows the generated schedule to be visually evaluated, its fulfillment to be monitored and the WC work to be simulated.

All the data from the scheduler data tables and the simulation model can be copied into Excel worksheet for further analysis.

4.2. Reports and logs

After the simulation experiment is completed and the simulation execution window is closed, the simulation results are saved in the resulting report in Excel format and in the 📁 logs folder as log files in text format. Each log in text format can be opened in Excel and detailed information on progress in the simulation can be viewed.

4.2.1. Resulting report

The resulting report contains information on the main outcome of the simulation and consists of the following sheets:

- "Experiment" sheet that contains the name of the simulation, the name of the project, the name of the scenario file and the path leading to it.
- "Production orders" sheet that contains information on the fulfillment of production orders.
- "WC state over period" sheet that contains information on the state and workload of Work Centers for the entire simulation period.
- "WC workload by months" sheet that contains monthly data on workloads at the Work Centers.

4.2.2. Log files

Log files are text files containing low-level information about the progress of the simulation. Log files can be used to generate detailed reports that reflect the dynamics of simulation and the structure of high-level indicators on the functioning of the production enterprise. Log files are generated by the simulation model upon completion of the corresponding simulation run.