# Models of the manufacturing system components

**Paweł Litwin**
**Rzeszów University of Technology**

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# Overview

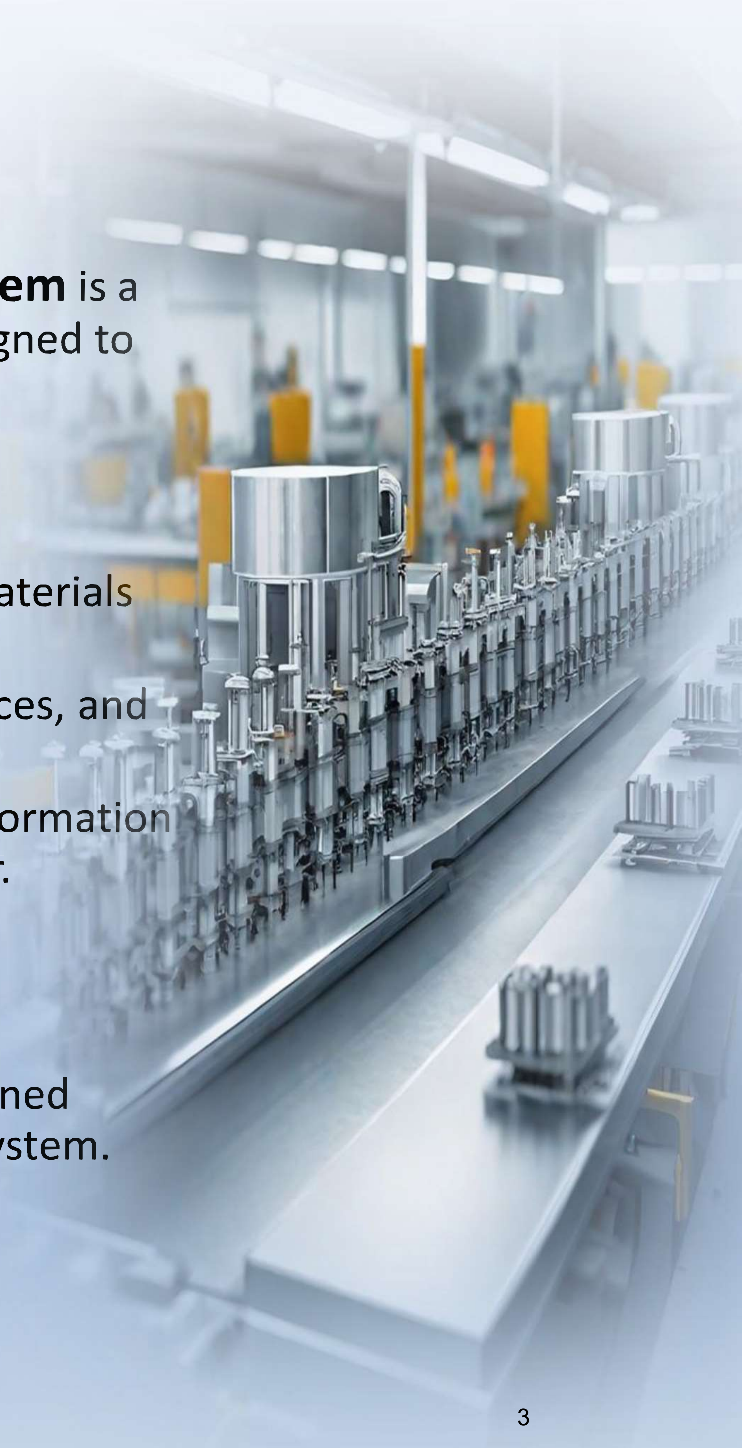
1. Introduction to Manufacturing Systems
2. Advantages of SD in Manufacturing Systems Modeling
3. Modeling the Machining Process in SD
4. Challenges and Limitations of SD

# What is a Manufacturing System?

Definition: **Manufacturing system** is a coordinated set of elements designed to produce goods or services.

## Key Elements:

1. **Input Vector**: Resources like materials and labor.
2. **Output Vector**: Products, services, and waste.
3. **Manufacturing Process**: Transformation of input vector into output vector.
4. **Management proces of the manufacturing system**.
5. F**low of materials, energy and information** between the mentioned elements of the manufacturing system.



# Role of System Dynamics in Manufacturing

- **System Dynamics (SD)**:
  A simulation-based methodology for modeling feedback loops, stocks, and flows.
- **Significance in Manufacturing:** SD provides frameworks to model production processes, facilitating enhanced decision-making and operational efficiency.
- **Modeling Capabilities:** Through simulation, SD models dynamic interactions, allowing manufacturers to anticipate outcomes and optimize resources.

# Components of System Dynamics

- **Feedback Loops:** Feedback loops are critical in SD, influencing system behavior by regulating resource flow and interactions.
- **Stock and Flow Structures:** Stock and flow structures represent inventory levels and their changes over time, essential for process modeling.
- **Continuous and Dynamic Systems:** SD models emphasize continuous, dynamic systems exhibiting ongoing changes driven by internal and external factors.

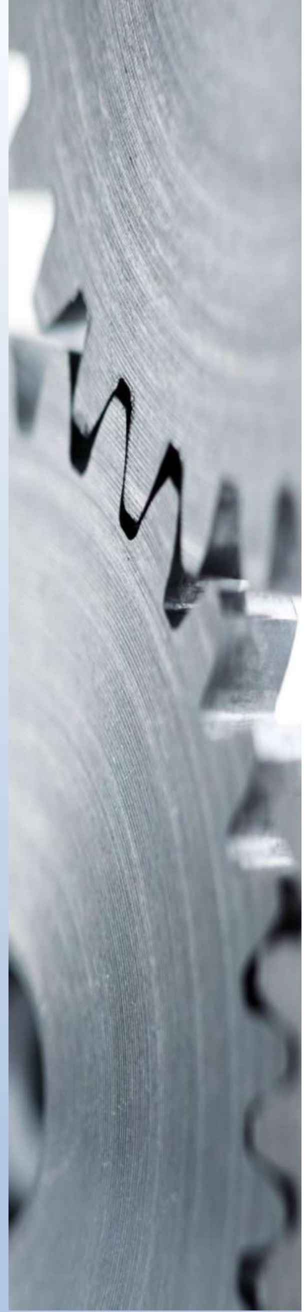
# Benefits of Using SD in Manufacturing

- **Flexibility**: Adapts to both continuous and discrete processes.
- **Efficiency**: Identifies bottlenecks and optimizes resource allocation.
- **Modeling Production Dynamics:** SD effectively captures complex production dynamics, enabling detailed analysis of constraints and resource utilization.
- **Enhancing Decision-Making:** The insights from SD models support proactive decision-making, optimizing operational strategies and outcomes.
- **Addressing Operational Challenges:** SD identifies potential bottlenecks and system behaviors, facilitating timely interventions in manufacturing processes.

# Manufacturing proces parameters for SD Implementation

**Data Requirements:**

- **Processing time (unit time), Tp** - the time required to perform a technological operation for the processed product or products.
- **Cycle time, Tc** - is the shortest time between the output of the technological operation of successive products. If n products are processed simultaneously in the operation (e.g. in heat or thermo-chemical treatment ) then Tc = Tp/n.
- **Available working time, AWT** - the time that can be used to carry out the operation. AWT is calculated as the time of the work shift minus planned breaks.
- **Transport operation time** - the time required to move a batch of products between successive technological operations.
- **Transport batch size** - the number of products moved in a transport operation.
- Delivery period - the interval between consecutive deliveries of materials for production.
- **Delivery volume** - the quantity of materials supplied for the production of products.
- **Work-in-process inventory, WIP** - the number of products between technological operations. In the SD method, WIP inventories are represented as products in the input and output trays of machine tools.



# Challenges and Limitations

1. Complexity: Requires comprehensive data and expertise.

2. Validation: Ensuring models reflect real-world behaviors.

3. Time-Intensive: Developing and simulating models requires resources.

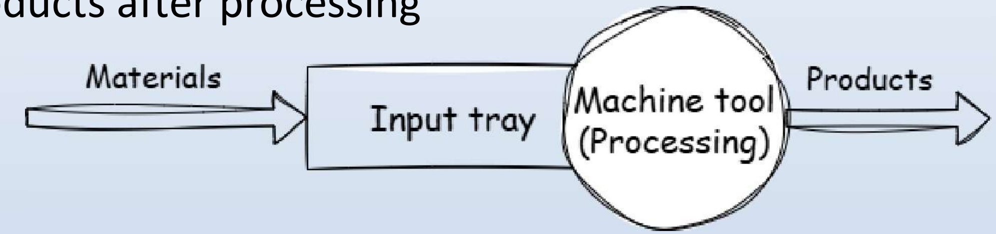
# Material Flow in Production Lines

- **FIFO, LIFO, FEFO Systems:** Rules governing material handling in manufacturing, enabling efficient inventory turnover and minimal waste.
- **Continuous Processing Assumption:** Modeling assumes uninterrupted machine operation for accurate representation of production dynamics across timeframes.

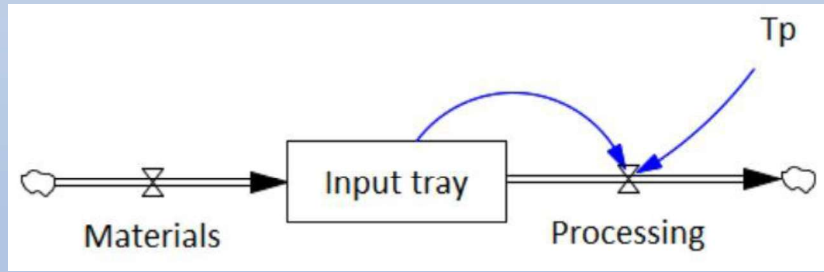
Storage and release of material from the tray is carried out according to one of the principles: FIFO, LIFO or FEFO. FIFO (First In First Out) assumes the flow of material according to the principle: “first in - first out”. The opposite flow principle is LIFO (Last In First Out) managed by the rule: “last in - first out”. The FEFO (First Expired First Out) principle, on the other hand, assumes that products are transferred in order of expiration date and is mainly used for foods.

# Case Study: Machine with Input Stock

In manufacturing processes, material processing is usually done using machine tools. Hence, consider a model of a machine tool in a production line, processing material taken from an input tray. The Materials flow represents the delivery of materials to the input tray of the machine tool . The Products flow represents the movement of products after processing




A model of an input bin machine tool developed in the systems dynamics method is shown below. The cloud-shaped elements define the boundaries of the system. This means that in the presented model, both the origin of the material (Material flow termination) and the destination of the products processed by the machine tool (Machine tool flow termination) are not important.




$$Processing = IF\ THEN\ ELSE(Input\_tray. \geq 1/Tp,\ 1/Tp\ ,\ 0\ )$$

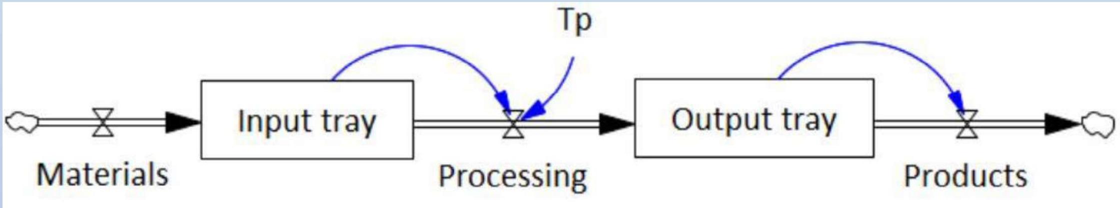
The SD method assumes a continuous flow. Hence, changes in the resource (in the case under consideration - Input_tray) are also continuous in nature.

# Continous and discrete Material Flow

When considering the processing of various products (units), their continuous flow often leads to certain problems. For example, if there are bars in the input tray for machining implemented in a turning operation, then at each time step a bar segment of size 1/Tp will be taken from the input tray. This section is simultaneously moved in the machining process to the system boundary. A problem arises when, after the turning operation, another technological operation requiring the use of another machine tool ( for example, grinding) is implemented. Then the grinding operation in the numerical simulation may start before the turning operation is completed, when the first bar sections after the turning operation move to the input tray of the grinding machine. It was found that this kind of interference could be prevented by implementing in the model a discretization of the material transfer to the next operation.

# Discrete Transfers Between Operations

- **Input Stock Functionality:** Input_Stock represents the current inventory level affecting processing capabilities based on material availability.
- **Processing Time Effect:** $T_p$ denotes the time taken for processing, influencing output rates in relation to input stock levels.
- **Output Generation Condition:** The formula generates output when sufficient stock is available, ensuring operational flow.




**Discrete Transfer of products is defined as**:

$Products = IF\ THEN\ ELSE(Outpur\ tray \geq 1, 1, 0),$

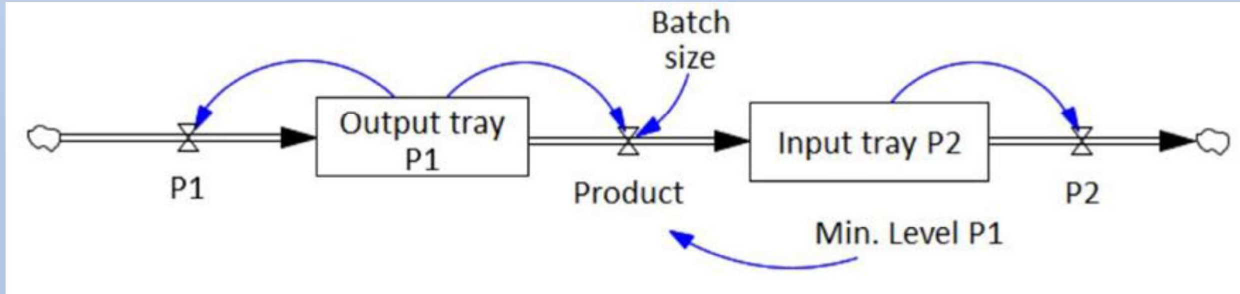
Output occurs only when Output tray meets the threshold, ensuring effective material flow regulation.

# Production Push vs. Pull Systems

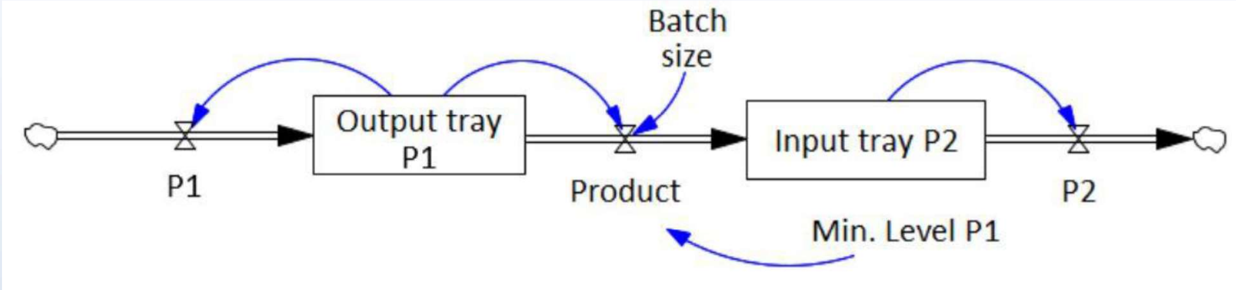
- **Push Production System:** Forecast-driven production schedules dictate output in push systems, regardless of immediate consumer demand.
- **Pull Production System:** Pull systems respond to actual consumption signals, optimizing resources based on demand fluctuations.
- Material in pull production is taken when the resources required to manufacture products are consumed. Hence, the transfer of material to the next operation requires sending information about the need for replenishment.

# Kanban in Pull Systems

- **Kanban System Overview:** The Kanban system optimizes material flow through Withdrawal Kanban and Production Order Kanban methodologies.
- **Withdrawal Kanban Functioning:** Withdrawal Kanban facilitates material requests based on actual consumption, enhancing inventory management practices.
- The relationship linking the output tray and the P1 process can be introduced to send information about the level of production required to replenish the output tray of the P1 process. In a two-card kanban system, the Production Order Kanban (POK) card is responsible for this information flow.



# Pull Systems Modelling




**The model determines the transfer of products** when the conditions are met:

*(Output_tray_P1 ≥ Batch_size) and (Input_tray_P2 < Min.Level_P2)*

**The flow of products** is then described by the relation:

*Product = IF THEN ELSE(Output_tray_P1 ≥ Batch_size AND Input_tray_P2 < Min.Level_P2, Batch_size , 0 )*

where:

*Output_tray_P1* - stock level (state) of the output tray P1,
*Input_tray_P2* - stock level (state) of the input tray P2,

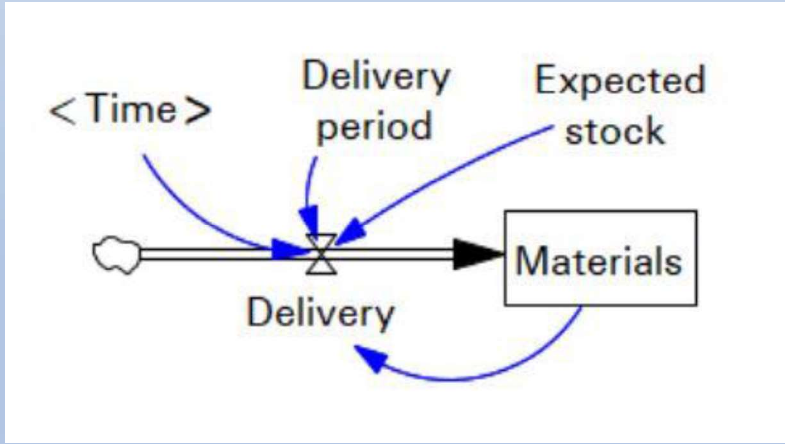
*Min.Level_P2* - minimum stock of the Input tray P2

# Cyclic Replenishment of Inventory

**Cyclic Replenishment Overview:** Cyclic replenishment ensures consistent inventory levels through regular scheduling of material deliveries to facilities.

**Replenishment Formula:** The formula employed is:

*Delivery = IF THEN ELSE(MODULO(Time, Delivery_period) = 0, Expected_stock - Materials, 0).*



# Operator Availability in Manufacturing

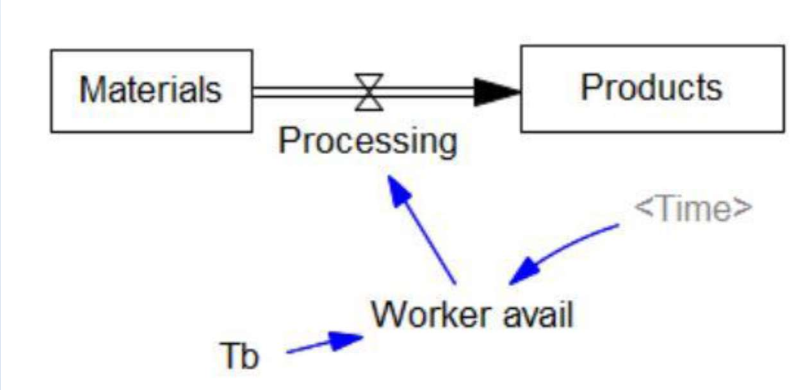
**Operator Availability Variables:** Determine availability using a binary variable, reflecting whether the operator is present or not.

**Work Schedule Integration:** Incorporate work schedules into models to dynamically adjust operator availability based on defined timeframes.

**Availability Formula:**

$$Worker\_avail = IF\ THEN\ ELSE(MODULO(Time,\ 480) \geq Tb\ :AND:\ MODULO(Time,\ 480) \leq Tb+30,\ 0,\ 1)$$

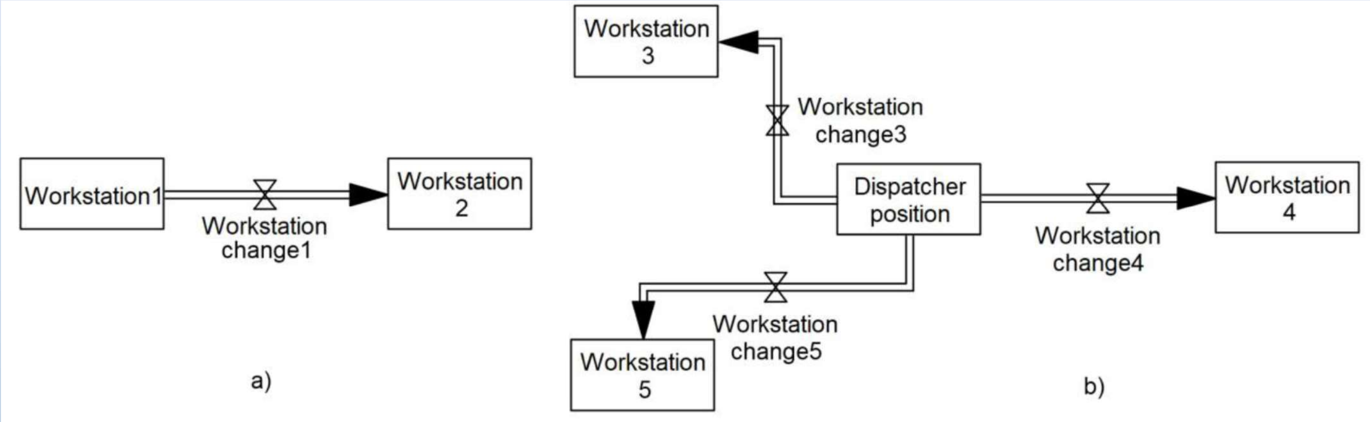
*where: Tb - break start time*




The worker is unavailable (has a break) when the remainder of the quotient of simulation time Time and 480 min. ≥ Tb and ≤Tb+30. For other values of the remainder of the quotient, the worker is available to operate the machine tool. The worker is not explicitly represented in the system model. The input variable DostPrac indicates only his availability to operate the machine tool.

# Single Operator Managing Multiple Machines

- **Direct Transition Mechanism:** Operators can directly transition between machines when specific conditions align, optimizing processing efficiency.
- **Dispatcher-Mediated Transition:** A dispatcher coordinates transitions when multiple operations require a single operator for efficient task allocation.




A worker in a direct job change (fig. a) occupies only the Workstation1 or Workstation2 service station. On the other hand, in the model with indirect job connection (fig. b), he can occupy Workstation3, Workstation4 and Workstation5 through the dispatcher's position. It should be emphasized that the flows (Workstation change1 - Workstation change5), have an indicated direction. However, the flow can take both positive and negative values. So, the employee moves in the indicated direction, as well as in the opposite direction.

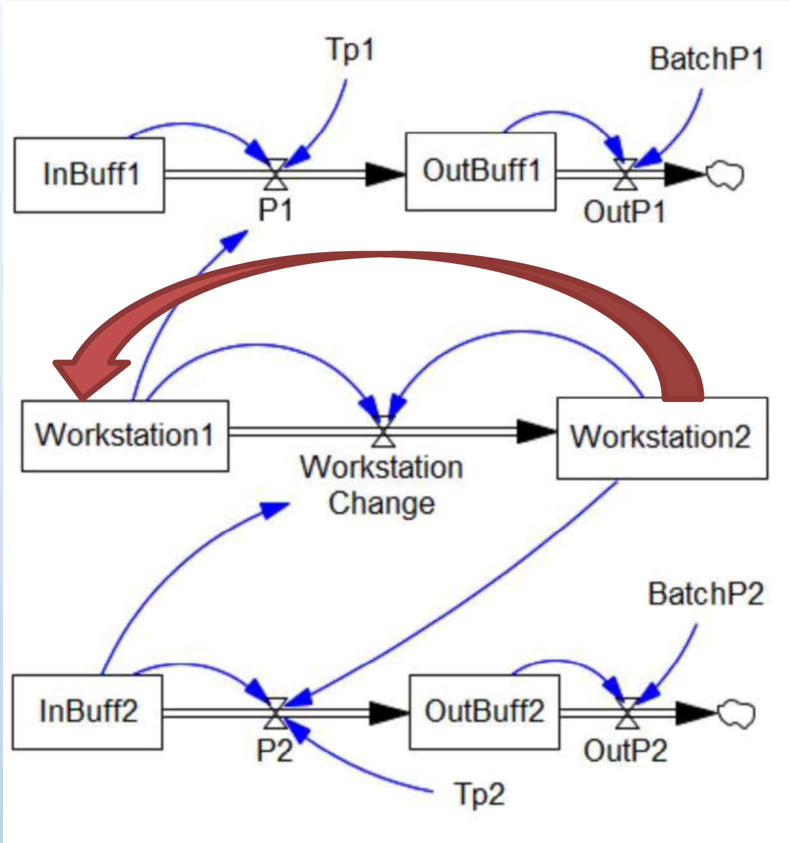
# Workstation Prioritization and Resource Constraints

The decision to transfer employees to a service position depends on certain developed rules. The basis of these rules - rules can be the following events:

- lack of material or products for processing,
- completion of processing of the required number of products,
- achievement of the maximum state of the output tray,
- failure of the machine tool,
- change of priority of tasks.

Consider the model of operating two machine tools (Workstation1 and Workstation2) by a single worker. Each machine tool has an input buffer and an output buffer. The machined products are dispensed using OutP1 and OutP2 flows, for which the transport batch size, BatchP1 and BatchP2, is specified.   The model thus represents two workstations (Workstation1 and Workstation2) connected by a WorkstationChange flow. The presence of a worker at the operating station is required for the machine tool to perform processing.

# SD Model Example: Multi-Workstation Setup (1)

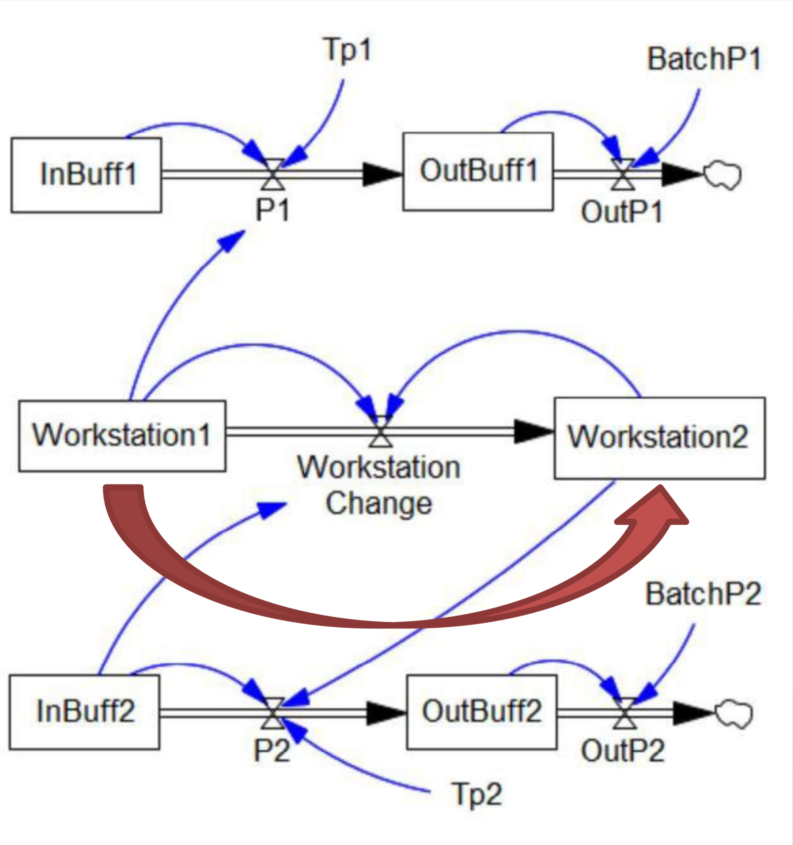



We can assume that the worker from Workstation2 (resource state of Workstation2 = 1) goes to Workstation1, when the conditions are met: InBuff2 = 0 - empty input buffer of Workstation2 machine tool, InBuff1 > 0 - P1 machine tool has material to process. For this case, the flow equation WorkstationChange has the form:

*WorkstationChange = IF THEN ELSE(InBuff2 = 0 : AND : InBuff1 >0 : AND : Workstation2 = 1, -1 , 0 ).*

For the movement of a worker from Workstation2 to Workstation1, the flow value WorkstationChange = -1. Thus, it indicates the direction of the flow opposite to the specified on the schema.

# SD Model Example: Multi-Workstation Setup (2)




The opposite situation is when the worker from Workstation1 (resource state of Workstation1 = 1) goes toWorkstation2. In that case the conditions are: InBuff2 > 0 - Workstation2 machine tool has material to process, InBuff1 = 0 - P1 machine tool input buffer is empty. For this case, the flow equation WorkstationChange has the form:

*WorkstationChange = IF THEN ELSE(InBuff2 > 0 : AND : InBuff1 = 0 : AND : Workstation1 = 1, 1 , 0 ).*

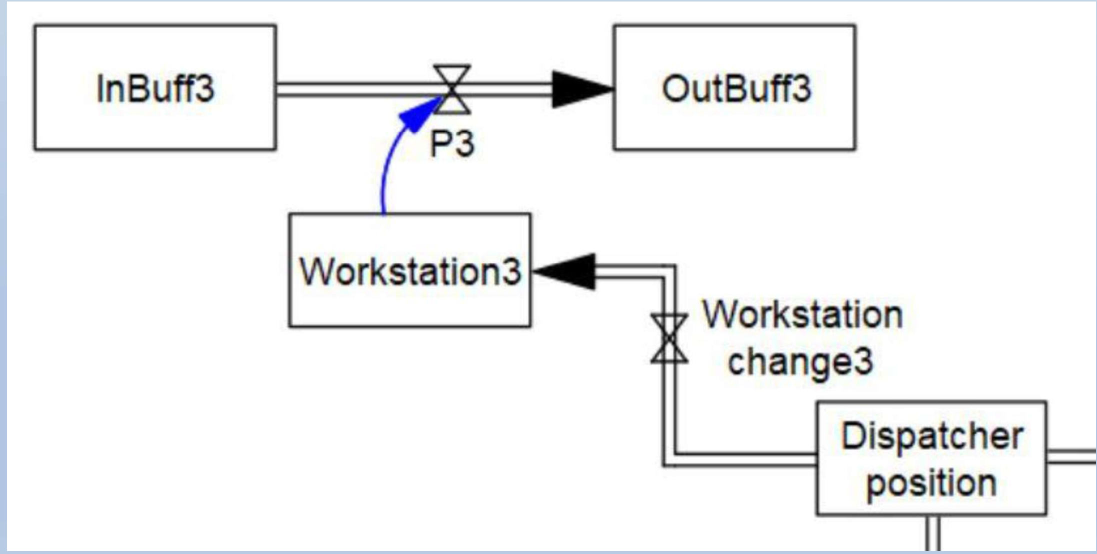
For the movement of a worker from Workstation1 to Workstation2, the flow value WorkstationChange = 1. Thus, it indicates the direction of the flow the same as specified on the schema.

# SD Model Example: Multi-Workstation Setup (3)

- The workstation change equations feature an additional check condition. It determines whether the position from which the worker is leaving is filled (Workstation1 resource state = 1). The introduced condition determines the flow between connected workstations. It reflects the operation of the containers between which the “token” representing the employee is passed.
- The WorkstationChange process should be determined by a single comprehensive dependency for controlling the movement of a worker in both directions. This dependency was obtained by combining the expressions presented earlier:
- *WorkstationChange = IF THEN ELSE(InBuff2 = 0 : AND : InBuff1 >0 : AND : Workstation2 = 1, -1 , IF THEN ELSE(InBuff1 = 0 : AND : InBuff2 >0 : AND : Workstation1 = 1, 1 , 0 ) ) ),*
- The developed relationship allows the implementation of the action for the satisfied criteria for the transition to Workstation1 - WorkstationChange=-1, while for the opposite case, when the criteria for the transition to Workstation2 are satisfied - WorkstationChange=1. For the other cases WorkstationChange = 0.

# SD Model Example: dispatcher-mediated work positions

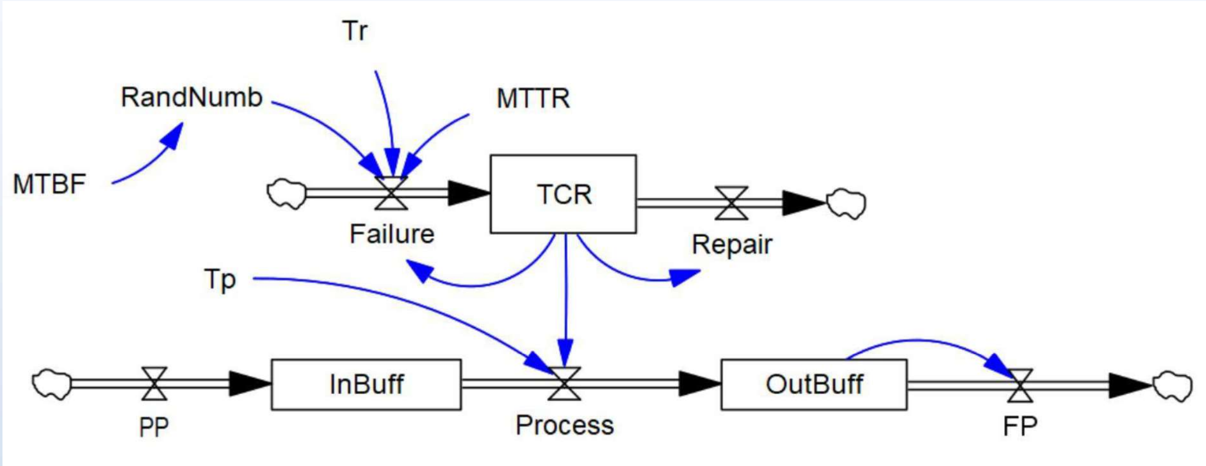
- When developing a model for dispatcher-mediated service positions, it is necessary to take into account that there may be 0, 1 or more employees at the position. In turn, the staffing of the service stations can take the value of 0 or 1. Workers move only from the dispatcher's station to the service station and from the service station to the dispatcher's station. Assuming the criteria as for direct station change, the WorkstationChange3 control equation is of the form:
- $WorkstationChange3 = IF\ THEN\ ELSE(\ Workstation3 = 0 \!:\ AND :\ InBuff3 > 0 :\ AND :\ DispatcherPosition \geq 1,\ 1\ ,\ 0\ )$
- The worker moves to the Workstation3 position when: Workstation3 = 0 - the Workstation3 position is not staffed, InBuff3 > 0 - there is material to be processed in the input tray of the P3 machine tool, and DispatcherPosition ≥ 1 - a worker is available at the dispatcher position. The rule for the transition of a worker from the Workstation3 to the dispatcher's position, and the comprehensive rule for controlling the WorkstationChange3 flow are presented similarly.



# Machine failure modelling

- Consider the operation of a machine tool whose failure does not lead to the production of nonconforming products. The failure causes the machine tool to stop and shut down until it is completely repaired. The impact of failure on the production process is described by indicators defined by the equipment manufacturer, among others:
- - MTBF - mean time between failures;
- - MTTR - mean time to remove failure .
- The developed failure occurrence model is presented for the operation of a machine tool with input and output trays. The introduced variable RandNumb takes the value of the generated random number indicating the time of failure occurrence. The Vensim program allows the generation of a random value for probability of distribution, among others: uniform, normal, Poisson, Weibull and exponential.

# Machine failure modelling




For Time ∈ (0, MTBF), one failure is assumed to occur. Thus, for the quotient of Time and MTBF, for a homogeneous probability distribution, a failure can be assumed to occur with probability P = 1/MTBF in any indicated time unit. For simulation time Time > MTBF, it is possible to generate subsequent failures using the MODULO function. After generating a failure, the Failure flow sends to the TCR (time to repair completion) resource a value expressing the mean time to repair (MTTR) according to the relation:

*Failure = IF THEN ELSE(GenLos>Time : AND : GenLos ≤ Time+1 : AND :TCR ≤ 0, MTTR , 0 ),*

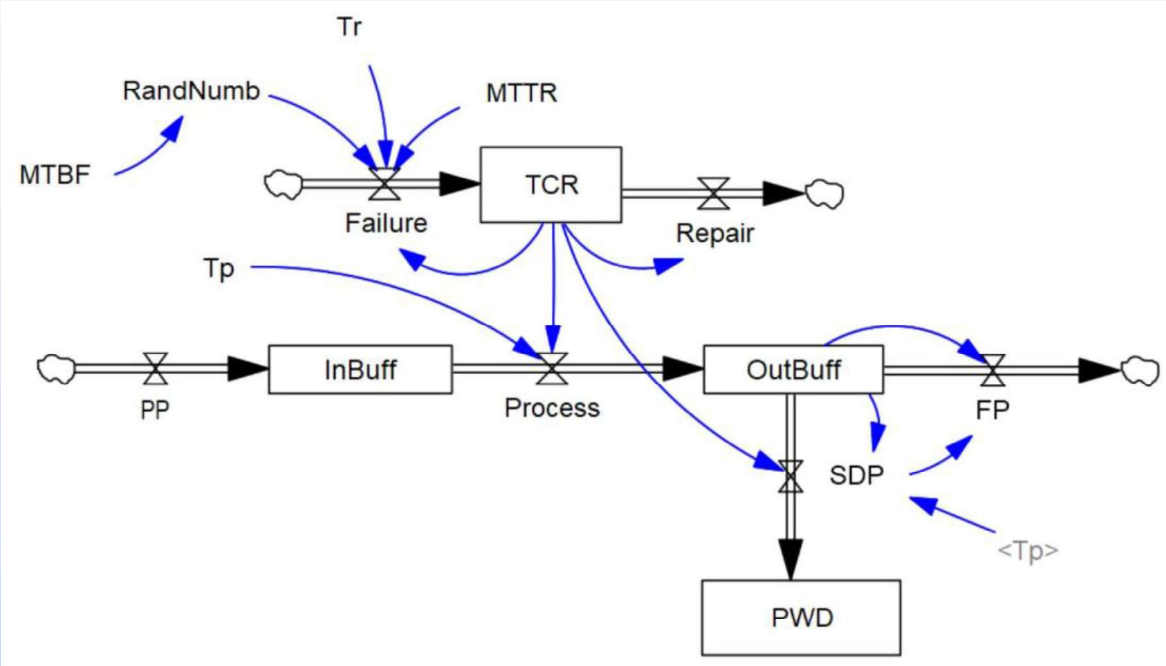
The relation determines the transfer to the TCR resource of the MTTR machine tool repair time only for the case when GenLos ∈ (Time, Time+1> and TCR ≤ 0 is generated. This means that the machine tool is not under repair at a given time. The elapsed repair time is determined by the relation.

*Repair = IF THEN ELSE(TCR > 0, 1 , 0 ),*

When TCR > 0, the Repair flow reduces the state of this resource by one in each simulation step. TCR > 0 also indicates that the machine tool is under repair and is not performing processing:

*Process = IF THEN ELSE(TCR>0, 0, 1/Tp )*

# Machine failure modelling




For failures in which the response time Tr > 0, the products processed to stop the machine tool may contain defects. The defective products are received from OutBuff and sent to the PWD resource (products with defects).

The SDP flow (separation of defective products) is active when the OutBuff contains the set required number of products and TCR > MTTR.

*SDP = IF THEN ELSE(*

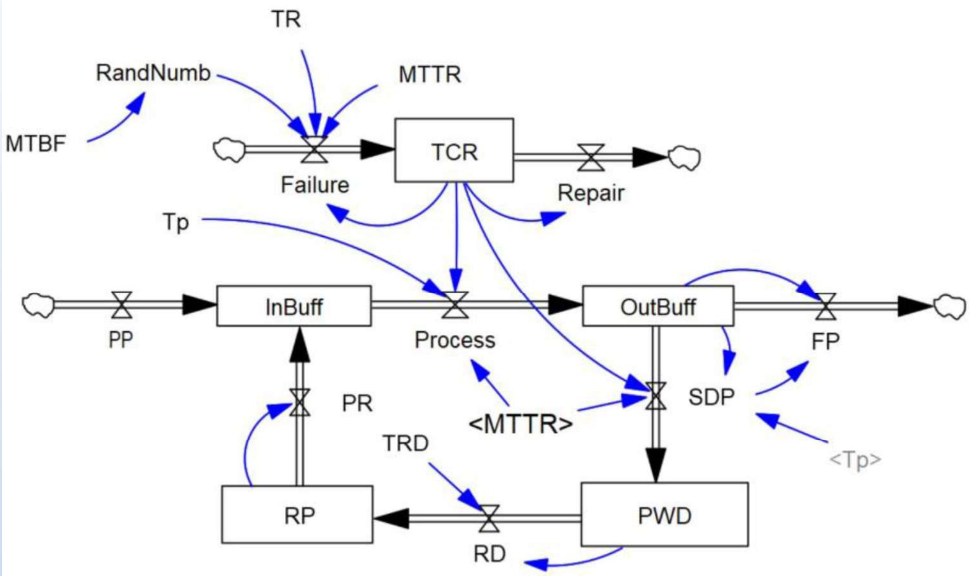
*OutBuff ≥ 1/Tp : AND : TCR > MTTR, 1/Tp , 0 ).*

The relationship that characterizes the FP flow (transfer of products to following processes). Items are sent when the Output Resource contains the required amount of material and the value of the SDP flow = 0.

It allows the assumption that items are sent when OutBuff contains the required amount of material and SDP = 0.

*FP = IF THEN ELSE(OutBuff ≥ 1 : AND : SDP = 0, 1 , 0 ).*

# Machine failure modelling




A model for transferring defective products for reprocessing, after repair and removal of defects (RD). The defect removal operation in the model is characterized by TRD (time to repair defects) and is implemented when the PWD resource contains the required number of products to repair, according to the relation:

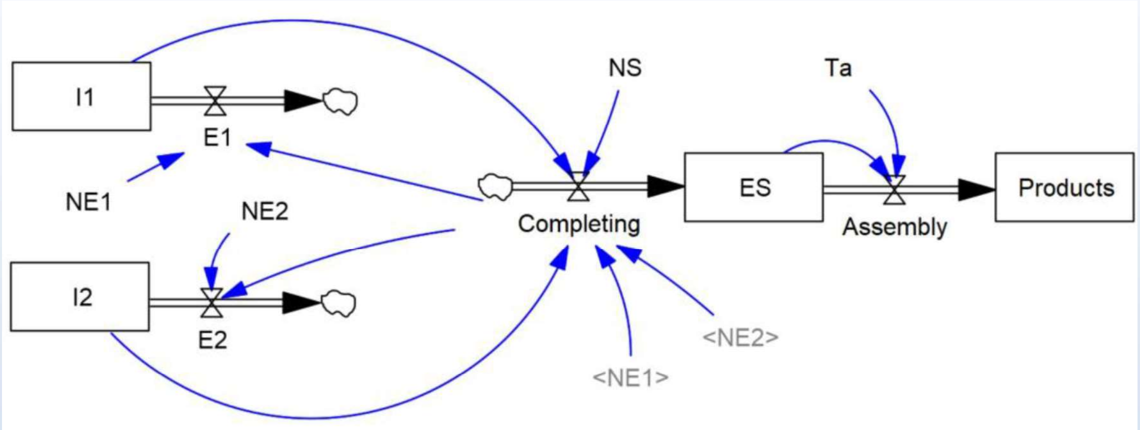
RD = IF THEN ELSE(PWD ≥ 1/TRD, 1/TRD , 0 ).

Product Re-processing (PR) flow retrieves products available in the RP resource and sends them to the input tray of the machine tool):

PR = IF THEN ELSE(WR ≥ 1, 1 , 0),

In the developed model of the repair process, the products after removal of defects are transferred to the machine tool that caused the defects. However, depending on the handling procedure, the PR flow may be directed to another designated machine tool.

# Assembly proces modelling




In a unit of time, a certain number of sets (NS) are created. The main component of the model is Completing. It performs a check on the availability of elements in resources I1 and I2 and determines the retrieval of the corresponding number of elements (NS * NE1 from resource I1 and NS * NE2 from resource I2). The element sets are transferred to the ES resource (element sets). It is also assumed that the time required to retrieve and transport the elements is included in the assembly time. The value of the Completing flow indicates the number of sets created (NS):

$Completing = IF\ THEN\ ELSE(I1 \geq NS*NE1\ :AND:\ I2 \geq NS*NE2,\ NS,\ 0\ ),$

When resource I1 ≥ NS*NE1 and resource I2 ≥ NS*NE2, NS sets are created. Otherwise, element sets are not created. The creation of sets reduces the resources of elements I1 and I2. The flows E1 and E2, which reduce the states of resources I1 and I2, respectively, are described by the relationship:

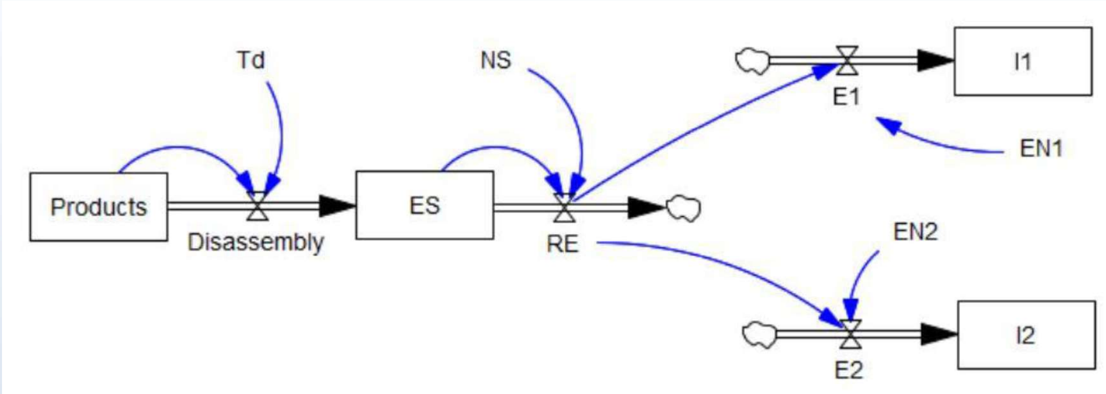
$E1 = Completing*NE1;\ E2 = Completing*NE2,$

The Assembly flow allows the collection of sets of elements and transformation into assembly units (Products):

$Assembly = IF\ THEN\ ELSE(\ ES \geq 1/Ta\ ,\ 1/Ta\ ,\ 0\ ),$

Where: ES - the inventory level of assembling sets, Ta - the assembly time.

# Disassembly proces modelling




The Disassembly flow fulfils the role of converting Products into element sets (ES). The basic parameter of this process is the disassembly time Td. The disassembly process is performed when the Products resource contains the required number of units for disassembly according to the equation:

$Disassembly = IF\ THEN\ ELSE(Products \geq 1/Td,\ 1/Td\ ,0\ ),$

where: Td - disassembly time.

The disassembly process leads to the storage of sets of items in the ES resource. With the number of these sets ES ≥ NS, it is possible for the flow RE to transfer the stored elements to the resources I1 and I2 according to the relation:

$RE = IF\ THEN\ ELSE(ZE \geq NS,\ NS\ ,\ 0\ ),$

where: RE - release of elements after disassembly, ES - stock of element sets, NS - number of element sets transferred.

The flow of sets of parts in flow RE is the basis for determining the number of elements transferred to the indicated storage, respectively for stock E1 and E2.

$E1 = RE * NE1;\ E2 = RE * NE2,$

Where: E1, E2 - flows of parts after disassembly, NE1, NE2 - number of parts in the set after disassembly.

# Parallel machining of products in a manufacturing process

Parallel machining of products in a manufacturing process
Performing the same technological operation simultaneously on multiple machine tools is used to improve productivity and reduce production time. Increasing the number of workstations carrying out the same technological process also leads to an increase in costs (e.g. employment of workers, purchase of machine tools).The parallel manufacturing model is distinguished by: splitting the flow of products, simultaneous execution of technological processes and joining the flows of manufactured products. The model of parallel realisation of technological operations is characterised by a structure similar to the assembly and disassembly models . It was assumed that the parallel operations will be independently fed (each operation independently replenishes the material stock). Thus, it will also be possible to operate the system when one of the processes is stopped (e.g. breakdown, lack of service).

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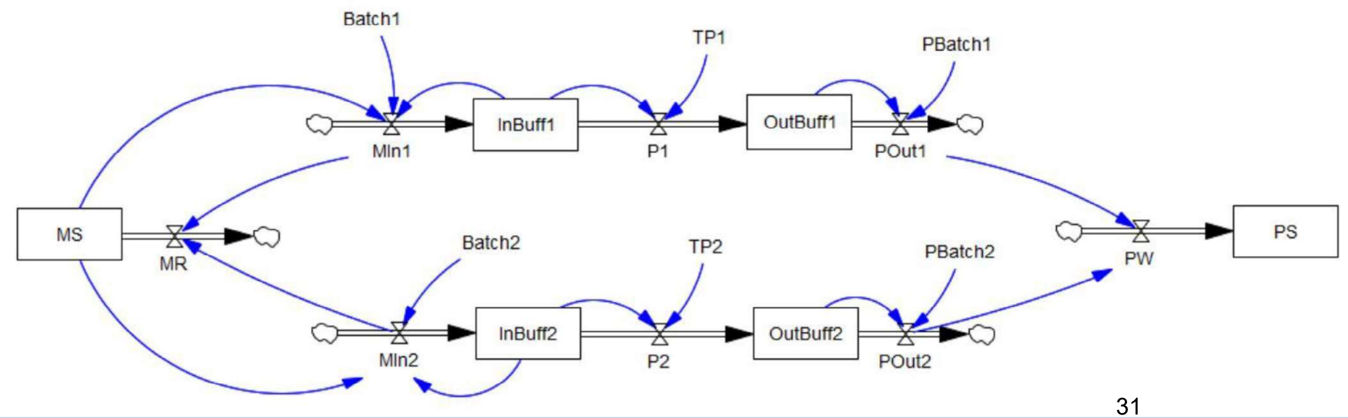

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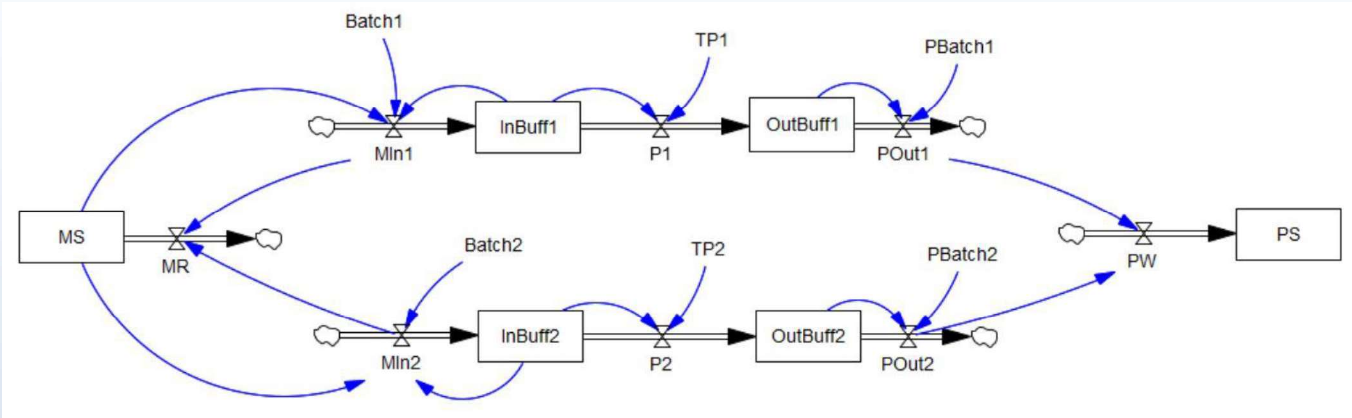



The magnitudes of the flows MIn1, MIn2 are defined by the relationships:

$MIn1 = IF\ THEN\ ELSE(MM > Batch1{:}AND{:}InBuff1<1,\ Batch1\ ,\ 0\ ),$

$MIn2 = IF\ THEN\ ELSE(MM > Batch2{:}AND{:}InBuff2<1,\ Batch2\ ,\ 0\ )$

where: MIn1, MIn2 - material input flow, Batch1,Batch2 - size of material transport batch taken, InBuff1, InBuff2 - stock status of input bin of process P1 and P2 respectively. For the material stock MS > Batch1 and for the input accumulator InBuff1 < 1, a batch of material is taken to the machine tool P1. The input flow relationship of machine tool P2 (MIn2) has an analogous design. The machine tool (P1, P2) performs processing when there is sufficient material in the input accumulator (InBuff1, InBuff2). Assuming that the time of a technological operation is Tp, then 1/Tp of this operation is performed per unit time. The relationship defining the processing performance for machine tool P1 takes the form:

$P1 = IF\ THEN\ ELSE(InBuff1 \geq 1/Tp1,\ 1/Tp1\ ,\ 0\ )$

Processed products are sent to the machine tools' output bins, OutBuff1 and OutBuff2. P1 is described by the relation:

$POut1 = IF\ THEN\ ELSE(OutBuff1 \geq PBatch1,\ PBatch1\ ,\ 0\ )$

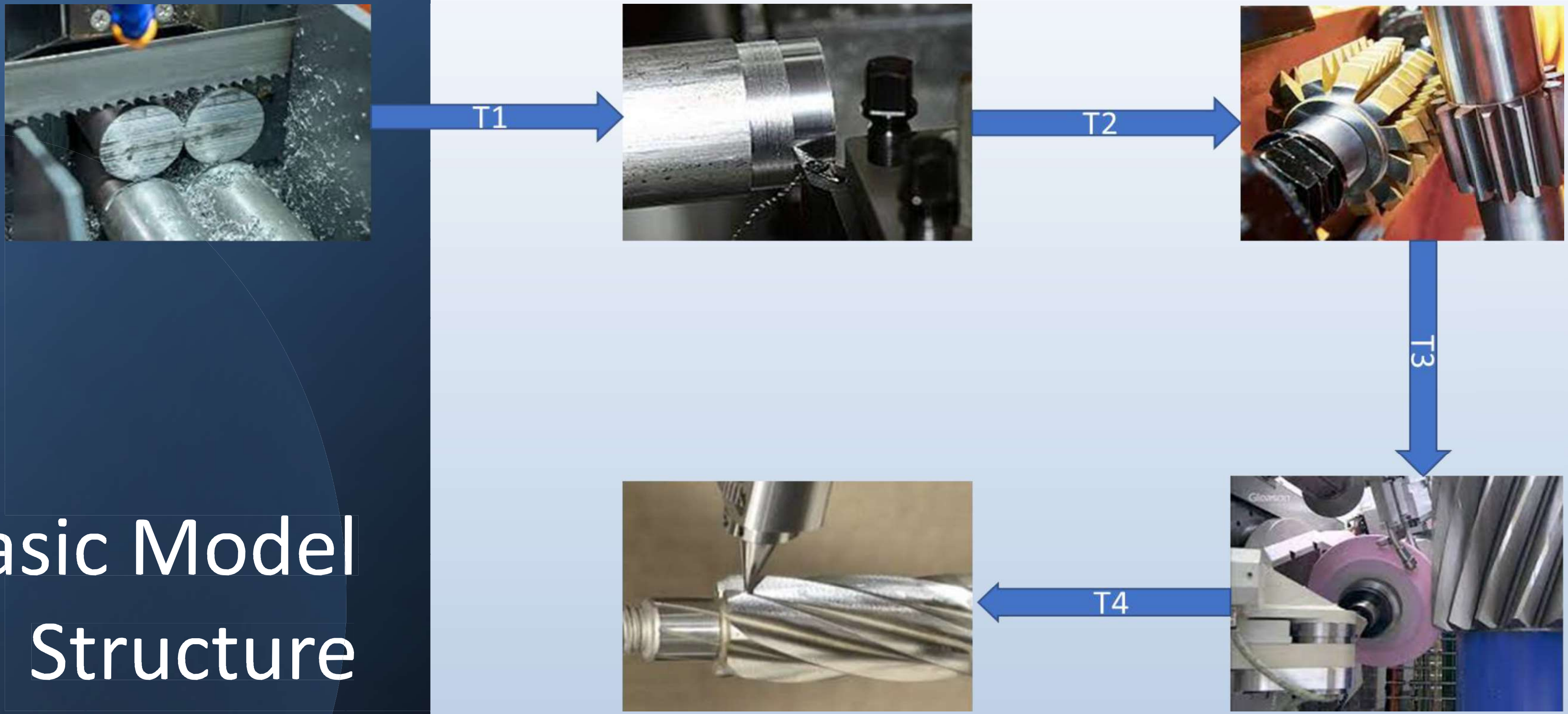
where: POut1 - output flow of products processed in process P1, PBatch1 - transport batch size of products.

The product acceptance flow (RP) is the sum of the product output flows POut1+POut2. Finished products are stored in the resource PS (product storage).

# Production Flow Organization

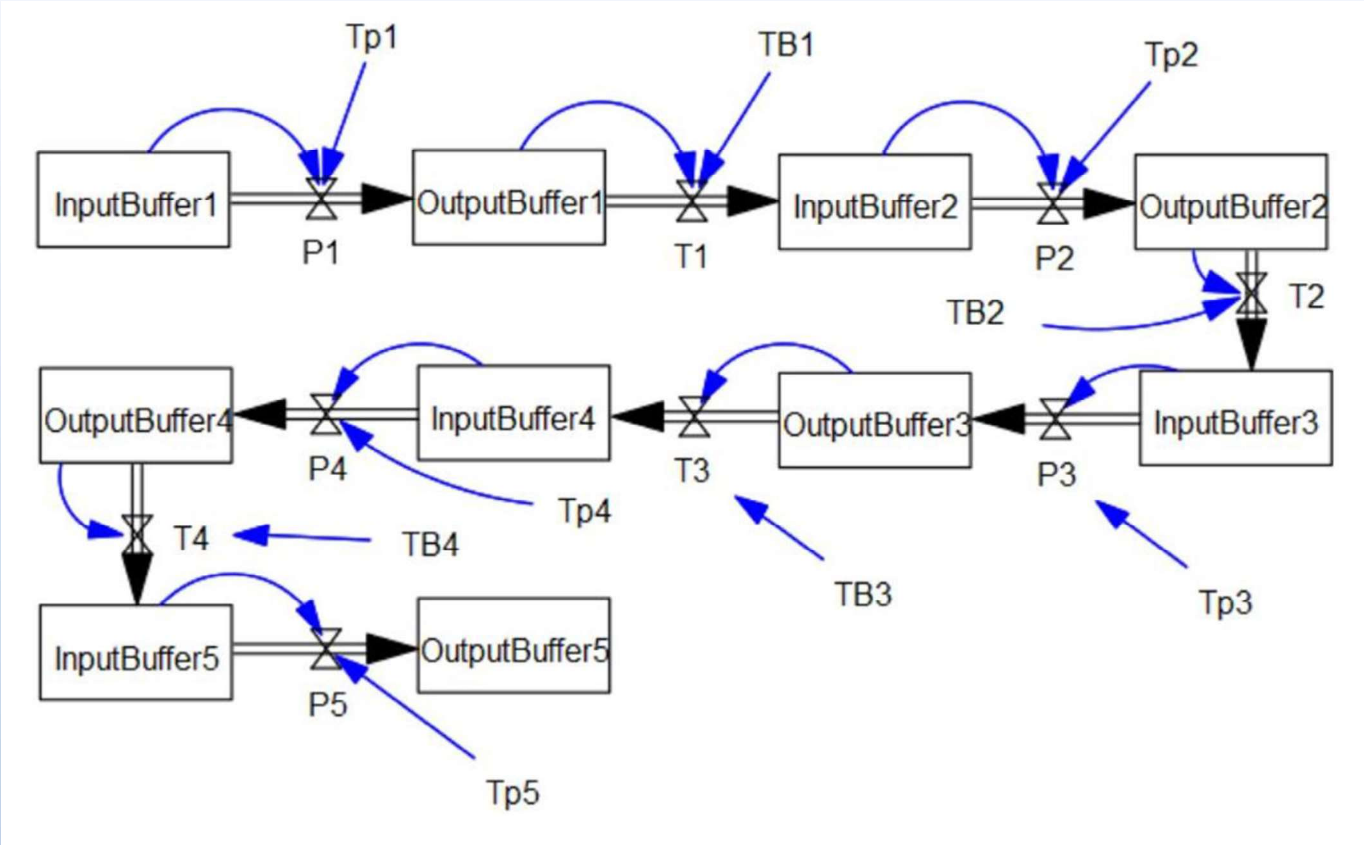
- **Serial Flow Structure:** Characterized by sequential operations, where completion of one step is required before the next begins.
- **Parallel Flow Structure:** Permits simultaneous operations, enhancing throughput but requiring careful management of resource allocation and synchronization.
- **Serial-Parallel Flow Structure:** Combines both serial and parallel elements, optimizing batches and transport while balancing workload across operations.

# Basic Model Structure




- **Operations Overview:** Manufacturing models include operations (P1 to P5) representing distinct processes within the production system.
- **Buffers in Dynamics:** Input/output buffers store items, influencing flow and allowing for integration of transport processes in modeling.
- **Transport Process Role:** Transport processes connect operations while discretizing flows, critically affecting overall efficiency and timing in manufacturing.

# Model Equations (Serial Process)




TB – Transport batch

Tp – Time of processing

**Processing Equation (Pn):**

Pn = IF THEN ELSE(InBuff.n ≥ 1/Tpn, 1/Tpn , 0).

**Transport Equation (Tn):**

Tn = IF THEN ELSE(OutBuff.n ≥ TBn, TBn , 0.

**Importance of Equations:** These equations encapsulate essential dynamic relationships critical for analyzing production flow.

# Simulation of Serial Flow

- **Serial Production Time Analysis:** Model simulations revealed a total processing time of 60 minutes for a batch of four products.
- **Efficiency Implications:** The significant processing duration emphasizes potential inefficiencies and delays inherent in serial workflow structures.
- **Transport Delay Impact:** Transport intervals contribute to overall cycle time, necessitating consideration in process efficiency optimization efforts.

| Process | Proc. Time | Batch processing time, min. |
|---|---|---|
| 1 | 3 | 1 2 3 4 |
| 2 | 4 | 1 2 3 4 |
| 3 | 2 | 1 2 3 4 |
| 4 | 2 | 1 2 3 4 |
| 5 | 3 | 1 2 3 4 |

The serial production flow can be presented in the form of a Gantt chart. The times of successive processes are given. The times of all transport operations are 1 minute.

When Batch size is 4 in all transportation processes then Batch processing time is 60 minutes.

# Simulation of Parallel Flow

- **Parallel Flow Simulation Results:** Simulations indicated a production time of 30 minutes for four products processed simultaneously in parallel.
- **Transport Time Contribution:** In parallel flow, transport time contributed approximately 13% to overall processing, influencing throughput significantly.
- **Throughput Visualization:** Tables illustrate throughput times, clearly contrasting parallel flow results against serial and variable batch methods.

| Process | Proc. Time | Batch processing time, min. |
|---|---|---|
| 1 | 3 | 1 2 3 4 |
| 2 | 4 | 1 2 3 4 |
| 3 | 2 | 1 2 3 4 |
| 4 | 2 | 1 2 3 4 |
| 5 | 3 | 1 2 3 4 |

The table shows production lead times with modified transport lot sizes. If 1 piece is transported between all processes then the production lead time will be 30 minutes.

# Serial-Parallel Flow

- **Characteristics of Serial-Parallel Flow:** This flow structure merges elements of both serial and parallel, enhancing operation efficiency when managed.
- **Logic Implementation Complexity:** Implementing this model introduces logic conditions that enhance adaptability but complicate simulation structures significantly.
- **Processing Time Comparison:** Serial-parallel flow yields improved processing times versus pure serial methods, yet operates slower than ideal parallel configurations.

| Process | Proc. Time | Batch processing time, min. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3 | 1 | | | 2 | | | 3 | | | 4 | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | 4 | | | | | 1 | | | | 2 | | | | 3 | | | | 4 | | | | | | | | | | | | | | | | | | |
| 3 | 2 | | | | | | | | | | | | | | 1 | | 2 | | | | | | 3 | | 4 | | | | | | | | | | | |
| 4 | 2 | | | | | | | | | | | | | | | | | | | 1 | | 1 | | | | | | | 1 | | 1 | | | | | |
| 5 | 3 | | | | | | | | | | | | | | | | | | | | | | 1 | | | 1 | | | | | 1 | | | 1 | | |

With transport batches equal 1-2-2-1 the production lead time is 35 minutes.

# Customization Potential

- **Customization for Scenarios:** SD models facilitate customization, allowing scenarios to adapt according to specific manufacturing requirements and conditions.
- **Adjusting Batch Sizes:** Flexibility in batch sizes enables systems to efficiently respond to varying production demands and market changes.
- **Refining Resource Allocations:** Dynamic adjustments in resource allocation enhance operational efficiency, addressing bottlenecks and optimizing performance metrics.
- **Impact of Transport Time:** Transport time significantly affects overall production time, emphasizing its role in efficient scheduling management.
- **Scheduling Implications:** Effective resource scheduling must account for transport times to minimize delays and optimize workflow continuity.

# Cost-Efficiency Analysis

- **Resource Management Challenges:** Incorporating transport time into models reveals challenges for resource allocation, necessitating strategic planning adjustments.
- **Balancing Transport and Production Costs:** SD methods help harmonize transport costs with production expenses, promoting overall cost-efficiency in manufacturing.
- **Strategies for Cost Efficiency:** Manufacturers can optimize layouts and batch processing to lower transport times while maintaining production flow.
- **Dynamic Resource Adjustments:** Continuous monitoring enables proactive resource adjustments, ensuring optimal trade-offs between transport and production efficiencies.

# Production flow simulation insights

- **Bottleneck Prediction:** SD model simulations enable early detection of potential bottlenecks, ensuring optimized resource flow and efficiency.
- **Throughput Optimization:** Real-world applications demonstrate how SD models enhance throughput by streamlining processes based on accurate data.
- **Comparative Analysis of Flows:** Tables illustrate performance metrics across serial, parallel, and variable batch configurations for clarity.
- **Simulation Findings Summary:** Key insights reveal processing times vary significantly across flow types, affecting production efficiency outcomes.
- **Significant Time Differences:** Examples show serial processing at 60 minutes while parallel achieves 30 minutes, impacting throughput notably.
- **Importance of Batch Size:** Adopting variable batch sizes can lead to 17% reduced times, optimizing production efficiency effectively.

# Decision-Making Factors

- **Production Volume Considerations:** Selecting flow configurations requires analyzing production volume to ensure alignment with manufacturing capacity needs.
- **Lead Time Evaluation:** Assessment of lead times is critical, influencing choice between serial, parallel or hybrid flow structures.
- **Resource Availability Assessment:** Understanding resource availability guides the selection of appropriate flow configurations, ensuring efficient utilization.

# Advantages of SD in Manufacturing Analysis

- **Predictive Power:** SD empowers manufacturers to forecast system behaviors, enabling proactive adjustments for various scenarios.
- **Flexibility in Scenario Testing:** Allows for rapid assessment of alternative strategies, enhancing adaptability to dynamic manufacturing environments.
- **Improved Decision-Making:** Insights derived from SD enable informed choices, aligning operational actions with strategic objectives.
- **Simplicity of Structure:** Constructing SD models is straightforward, facilitating easier interpretation and analysis of manufacturing processes.
- **Enhanced Production Efficiency:** Utilizing SD models boosts overall efficiency by optimizing resource allocation and minimizing process bottlenecks effectively.

# Challenges in SD Modeling

- **Challenges of Flow Assumptions:** Modeling complexities arise from choosing between continuous and discrete flow assumptions in system dynamics.
- **Impact on Accuracy:** Inconsistent flow assumptions can significantly impact model accuracy and operational effectiveness in manufacturing.
- **Hybrid Modeling Approaches:** Integrating both continuous and discrete elements offers a comprehensive solution to modeling challenges in SD.

# Future Applications

- **Future of SD in Industry 4.0:** SD modeling will adapt to Industry 4.0, integrating data analytics for real-time system adjustments.
- **Adaptive Manufacturing Systems:** Anticipated advancements will enhance SD's role in developing adaptive systems responding dynamically to changes.
- **Smart Systems Integration:** The integration of IoT with SD models will revolutionize monitoring processes and optimizing manufacturing decisions.
- **Long-term Strategic Value:** Investing in System Dynamics fosters long-term strategic advantages, adapting to evolving technological landscapes effectively.

# Conclusion

**System Dynamics provides a framework for analyzing and improving manufacturing systems:**

- **Optimizing Production Processes:** System Dynamics enhances understanding of production processes, affirming its value in operational efficiency improvement.
- **Insights on Flow Structures:** The presentation illustrated various flow structures, elucidating their implications for cost-effectiveness and flexibility.
- **Strategic Decision-Making Advantages:** SD models empower decision-making through simulation insights, facilitating informed adaptations to manufacturing strategies.

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