Lecture 2

Discrete Production Plants

Introduction

A discrete production process is the assembly of pieces and parts into products and the product result as a discrete entity. Discrete processes deal with material that can be counted. The equipment used in the process do not work in a steady state mode, but rather in a startup – operate – shut down mode.

An example of a discrete production process is the automotive industry, e.g. the production of cars, see Figure 1. The production line starts with the truck coming in with raw material such as metallic sheets. The first work cell performs Stamping. A stamping die is a specialized tool used to cut or shape materials using a press. The second work cell is the Body in white, in which the remaining activities in the production of a vehicle body are performed. After Body in White, the Paintwork takes place; here the vehicle body is painted in the correct color. The next to last work cell is the Body assembly where the interior of the car is installed, e.g., dashboard, gear, seats and doors. After inspection, the cars are loaded on a truck for shipment to the retailer or customer.

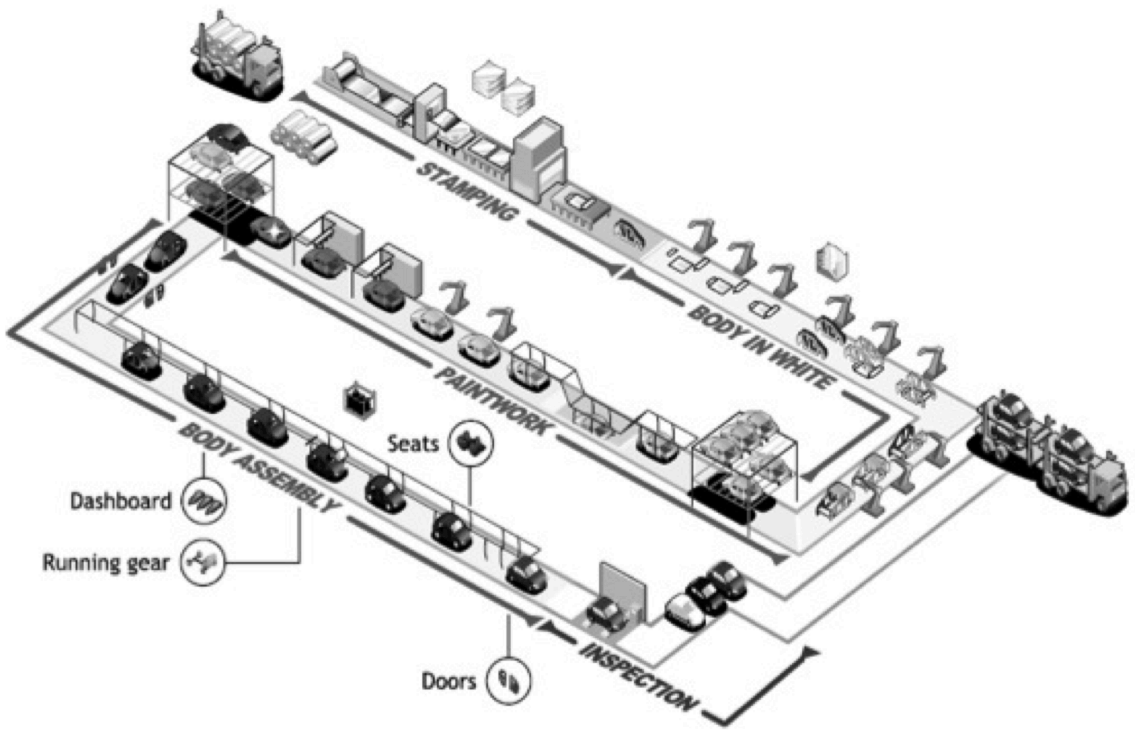


Figure 1: A schema of a discrete production plant.

There are a number of characteristics typical to discrete processes:

- The product is a discrete entity.
- Assembly-oriented production.
- Staged production through work cells
- Well-defined production runs.
- The process is most often “visible”.
- The equipment operates in on-off manner.
- The production process is sequential.

Control of Discrete Production Plants

Discrete manufacturing is typically assembly-line oriented. It involves the progressive assembly of finished products via a number of work cells, each providing a predefined set of mechanical operations. The equipment performing these operations operates in on-off manner. In order to structure the on-off of the machines sequential control languages are used.

The basic device invented for control of discrete production processes is the automatic switch and interconnected sequences of automatic switches. The first automatic switch to be extensively used for control of discrete production processes was the electromechanical relay, see Figure 2. The electromechanical relays were typically assembled on relay panels in a manner that would accomplish the desired automation steps, referred to as “relay ladders”.

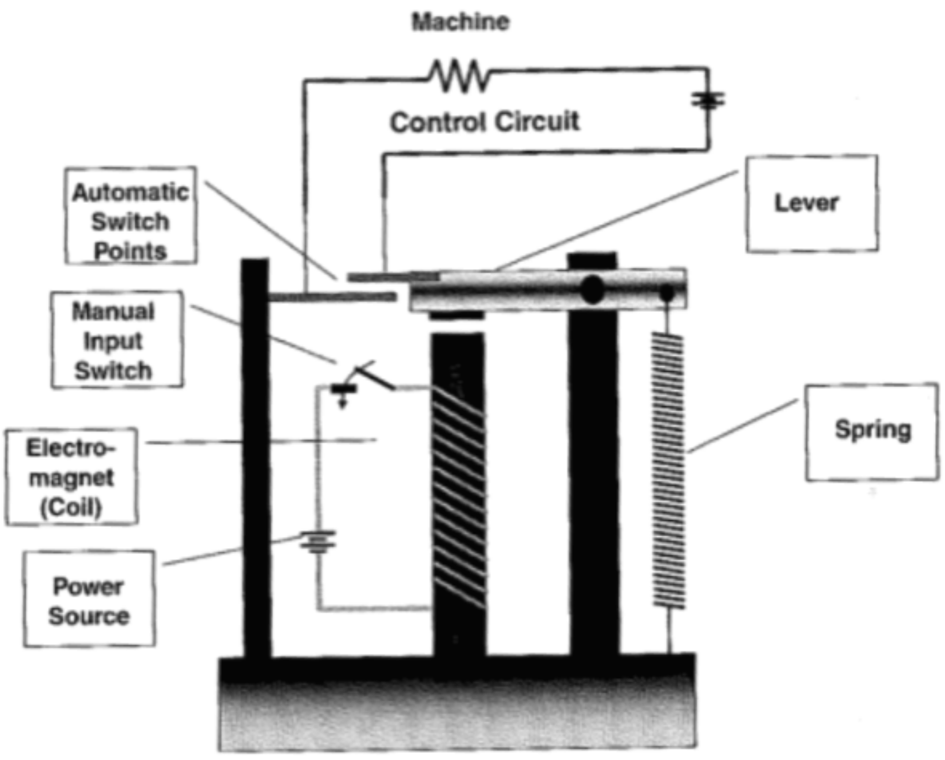


Figure 2: Electromechanical relay

Formal specification languages and formal modeling techniques are used to describe the behaviour of the equipment and/or production process. Formal analysis techniques are then used to verify certain critical properties. A number of approaches have been developed. They are based on; logics, finite state machines, and Petri Nets.

There are different tools and languages for implementation of discrete controllers. With better abstraction and structuring possibilities it is easier to get a good overview of the control problem and the implementation is drastically simplified. Most of these tools and languages are graphical programming languages. Grafcet is one example of such a language. Grafcet is now part of the IEC 1131-3 standard (later renamed IEC 61131-3), under the name Sequential Function Charts (SFC). JGrafchart is a toolbox based on Grafcet, implemented in Java. JGrafchart was developed at Department of Automatic Control, LTH, Lund University.

Logic

The concept used in the construction of relay ladders is boolean logic. In boolean logic, the variables are either true or false. Boolean logic is named after George Boole (1815-1864), who first defined an algebraic system of logic in the mid-19th century. Boolean logic is based on three operations; and, or, not.

Three types of operations			
AND	$a \cdot b$	*a* and *b*	$a \wedge b$
OR	$a + b$	*a* or *b*	$a \vee b$
NOT	$\bar{a}$ $(or\ a')$	not *a*	!a

The operations can be represented by graphical symbols. Figure 3 shows the symbols, the American representation to the right and the Swedish representation to the left.

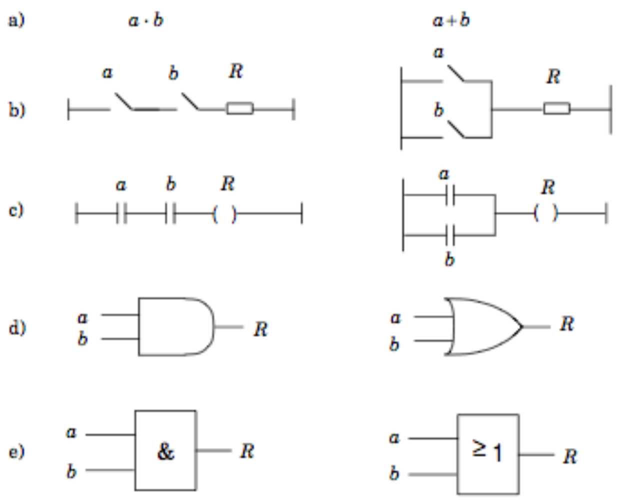


Figure 3: Boolean logic symbols

In logic the commutative, associative, distributive laws and De Morgan's law are used.

Commutative	$a \cdot b = b \cdot a$
Associative	$a \cdot (b \cdot c) = (a \cdot b) \cdot c$
Distributive	$a \cdot (b + c) = a \cdot b + a \cdot c$
De Morgan	$\overline{a + b} = \bar{a} \cdot \bar{b}, \qquad \overline{a \cdot b} = \bar{a} + \bar{b}$

In the 1960s the digital computer technology started to be popular for many applications, so also for the construction of relay ladders, this was referred to as "Programmable Logic Controllers (PLC)". The initial language of PLC was called ladder logic.

Today there exist an international standard, IEC 1131-3, for PLC programming languages. It specifies the syntax, semantics and display for the following PLC programming languages:

- Ladder diagram
- Structured text
- Instruction list
- Function Block Diagram
- Sequential Function Charts

Finite State Machines

The classical models for describing sequential systems are state machines. Two different types exist; Mealy machines and Moore machines. The output from a Mealy-machine depends on the internal state and the input whereas the output from a Moore machine depends only on the internal state.

In Figure 4 a Mealy-machine (left) and the corresponding Moore-machine (right) are shown. The two state machines have two inputs, a and b, and two outputs, z0 and z1.

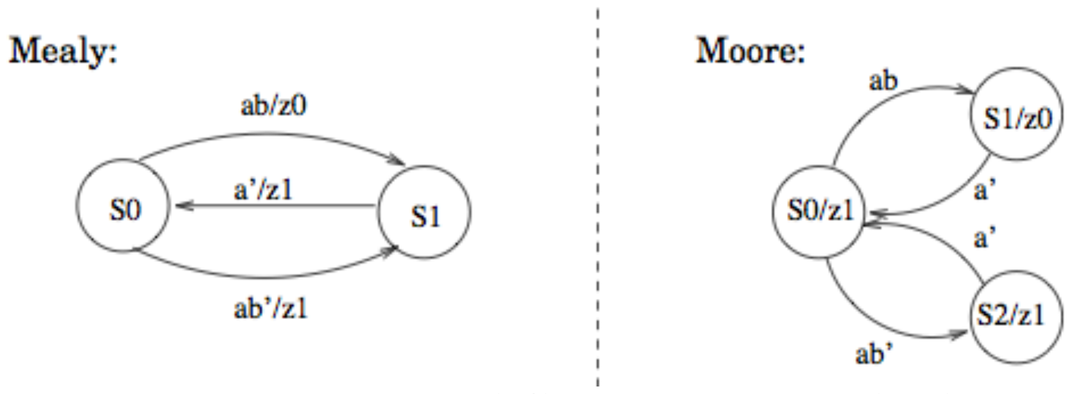
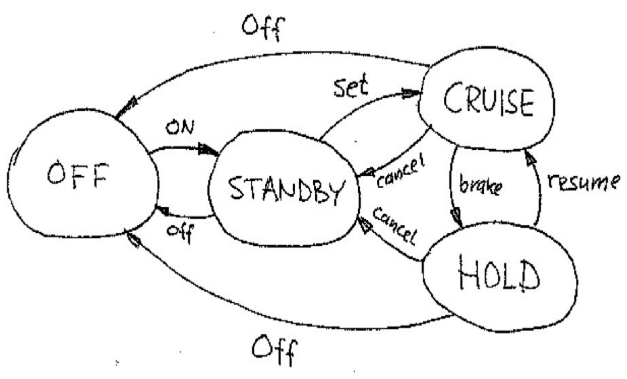


Figure 4: A Mealy-machine (left) and a Moore-machine (right).

A common application in today's vehicles is the cruise control. The cruise control system has a human-machine interface that allows it to communicate with driver to communicate with the system. There are many ways to implement this system; one version is illustrated by the finite state machine in Figure 5. When the driver sets the speed of the vehicle, the vehicle goes into the Cruise state. When the vehicle is in the Cruise state, the driver can go back to manual driving by giving the command cancel. If the driver hits the breaks while being in the Cruise state, the vehicle reduces the speed. When the driver let go of the break the car goes back to the Cruise state and the previous set speed. The driver also has the option of completely switching the Cruise controller off.



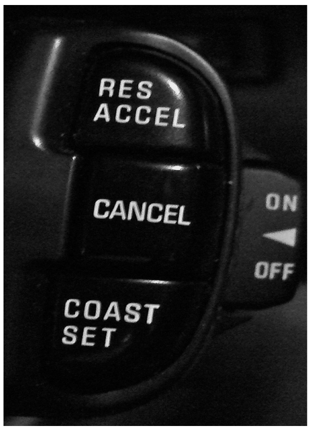


Figure 5: The state machine of a cruise controller (left) and the operator commands in the vehicle.

Petri Nets

Petri nets were proposed by the German mathematician Carl Adam Petri in the beginning of the 1960s. Petri wanted to define a general purpose graphical and mathematical model describing relations between conditions and events. The mathematical modeling ability of Petri nets makes it possible to set up state equations, algebraic equations, and other models governing the behavior of the modeled system. The graphical feature makes Petri nets suitable for visualization and simulation.

The Petri net model has two main interesting characteristics. Firstly, it is possible to visualize behavior like parallelism, concurrency, synchronization and resource sharing. Secondly, there exists a large number of theoretical methods for analysis of these nets. Petri nets can be used at all stages of system development: modeling, mathematical analysis, specification, simulation, visualization, and realization. Petri nets have been used in a wide range of application areas, e.g., performance evaluation, distributed database systems, flexible manufacturing systems, logic controller design, multiprocessor memory systems, and asynchronous circuits.

Petri nets have during the years been developed and extended and several special classes of Petri nets have been defined. These include, e.g.: generalized Petri nets, synchronized Petri nets, timed Petri nets, interpreted Petri nets, stochastic Petri nets, continuous Petri nets, hybrid Petri nets, coloured Petri nets, object-oriented Petri nets, and multidimensional Petri nets.

A Petri net (PN) has two types of nodes: places and transitions see Figure 6. A place is represented as a circle and a transition is represented as a bar or a small rectangle. Places and transitions are connected by arcs. An arc is directed and connects either a place with a transition or a transition with a place, i.e., a PN is a directed bipartite graph. A transition without an input place is called a source transition and a transition without an output place is called a sink transition.

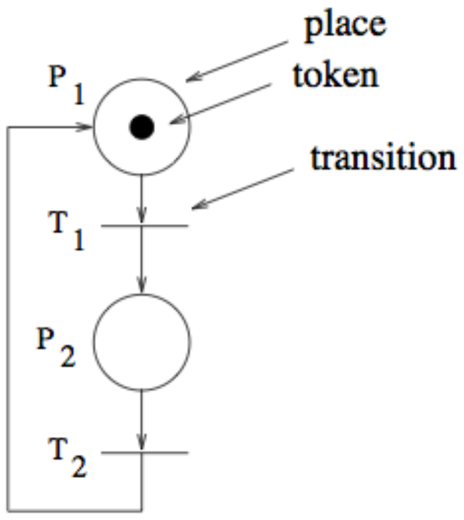


Figure 6: Petri Net

Systems with concurrency can be modeled with Petri nets using the and-divergence and the and-convergence structure, see Figure 7 (left). Systems with conflicts or choices can be modeled using the or-divergence and the or-convergence structure, see Figure 7 (right).

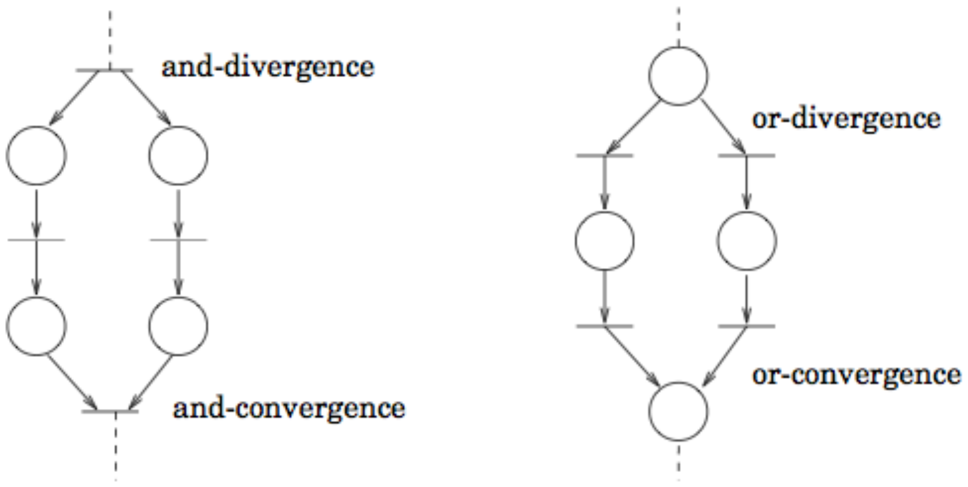


Figure 7: Concurrency and Conflict

A transition is enabled if each of its input places contains at least one token. An autonomous PN is a PN where the firing instants are either unknown or not indicated whereas a non-autonomous PN is a PN where the firing of a transition is conditioned by external events and/or time.

An enabled transition in an autonomous PN may or may not fire. An enabled transition in a non-autonomous PN is said to be fireable when the transition condition becomes true. A fireable transition must fire immediately. The firing of a transition consists of removing one token from each input place and adding one token to each output place of the transition. The firing of a transition has zero duration.

Petri Nets can be analyzed with respect to several properties:

- Live: No transitions can become unfireable
- Deadlock-free: Transitions can always be fired
- Bounded: Finite number of tokens

The analysis methods are:

- Reachability methods – exhaustive enumeration of all possible markings
- Linear algebra methods – describe the dynamic behaviour as matrix equations
- Reduction methods– transformation rules that reduce the net to a simpler net while preserving the properties of interest

Other types of Petri Nets are

- Generalized Petri Nets: Weights associated to the arcs
- Times Petri Nets: Times associated with transitions or places
- High-Level Petri Nets: Tokens are structured data types (objects)
- Continuous & Hybrid Petri Nets: The markings are real numbers instead of integers. Mixed continuous/discrete systems

Petri nets can conveniently be used to model systems with e.g., concurrency, synchronization, parallelism and resource sharing. The graphical nature of Petri nets also makes them suitable to use for visualization and simulation of systems. In addition to this, the nets can be theoretically analyzed with different analysis methods.

Grafcet

Grafcet was proposed in France in 1977 as a formal specification and realization method for logical controllers. The name Grafcet was derived from "graph", since the model is graphical in nature, and "AFCET" (Association Francaise pour la Cybernetique Economique et Technique), the scientific association that supported the work.

During several years, Grafcet was tested in French industries. It soon proved to be a convenient tool for representing small and medium scale sequential systems. Grafcet was therefore introduced in the French educational programs and proposed as a standard to the French association AFNOR where it was accepted in 1982. In 1988 Grafcet, with minor changes, was also adopted by the International Electro-technical Commission (IEC) as an international standard named IEC 848. In this standard Grafcet goes under the name Sequential Function Chart (SFC). Seven years later, in 1995, the standard IEC 1131-3, with SFC as an essential part, arrived. The standard concerns programming languages used in Programmable Logic Controllers (PLC). It defines four different programming language paradigms together with SFC. No matter which of the four different languages that is used, a PLC program can be structured with SFC.

Because of the two international standards, Grafcet, or SFC, is today widely accepted in industry, where it is used as a representation format for sequential control logic at the local PLC level.

Grafcet has a graphical syntax. It is built up by steps, drawn as squares, and transitions, represented as bars. The initial step, i.e., the step that should be active when the system is started, is represented as a double square. Grafcet has support for both alternative and parallel branches, see Figure 8.

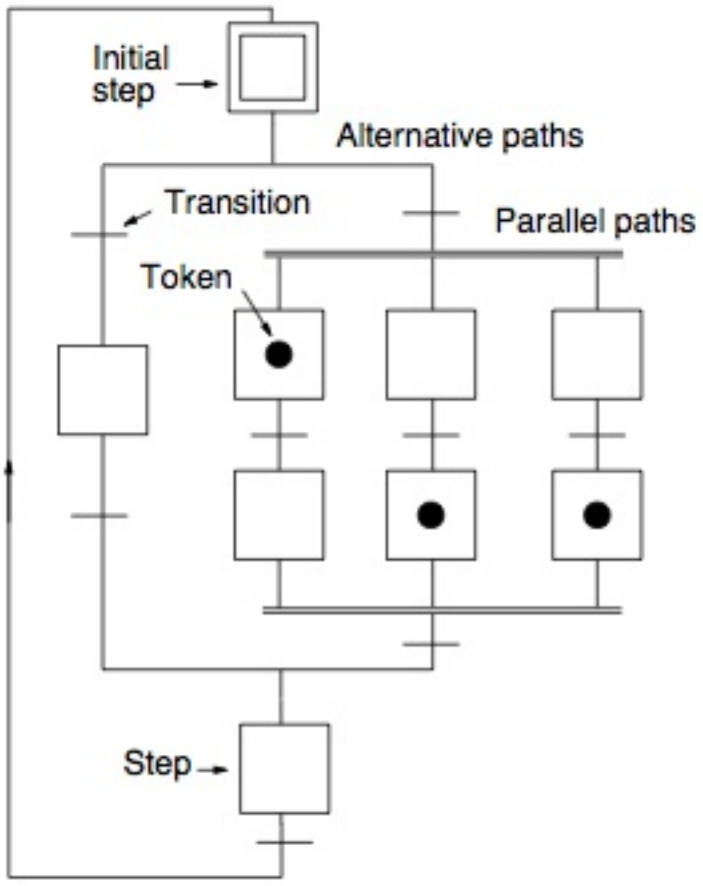


Figure 8: Grafcet graphical syntax.

A step can be active or inactive. An active step is marked with one (and only one) token placed in the step. The steps that are active define the situation or the state of the system. To each step one or several actions can be associated. The actions are performed when the step is active.

Transitions are used to connect steps. Each transition has a receptivity. A transition is enabled if all steps preceding the transition are active. When the receptivity of an enabled transition becomes true the transition is fireable. A fireable transition will fire immediately. When a transition fires the steps preceding the transition are deactivated and the steps succeeding the transition are activated, i.e., the tokens in the preceding steps are deleted and new tokens are added to the succeeding steps.

There are two major categories of actions: level actions and impulse actions. A level action is modeled by a binary variable and has a finite duration. The level action remains set all the time while the step, to which the action is associated, is active. When the step is deactivated, the action is reset. A level action may be conditional or unconditional. An impulse action is responsible for changing the value of a variable. The variable can, but must not, be a binary variable. An impulse action is carried out as soon as the step changes from being inactive to active. A variable representing time may be introduced to create time-delayed actions and time-limited actions. A level action can always be transformed into a set of impulse actions.

In Figure 9 (left) two steps, x1 and x2 are shown. A level action, A, is associated with the upper step and an impulse action, B*, is associated with the lower step. In the same Figure (right) an example is given describing the activation and deactivation of the two steps together with the duration of the two actions.

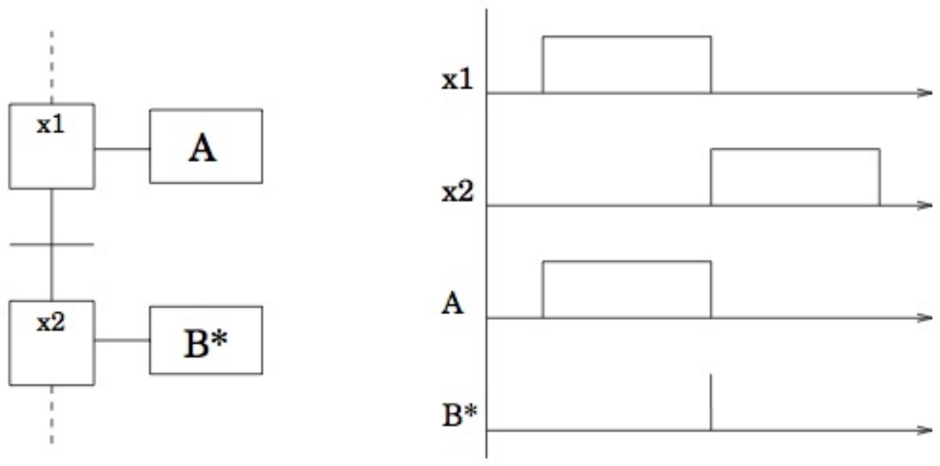


Figure 9: Level and Impulse actions.

A situation can be stable or unstable. If the transition following a step is immediately fireable when the step becomes active, the situation is said to be unstable. An impulse action is carried out even if the situation is unstable whereas a level action is performed only if the situation is stable. Between two different external events it is assumed that there is always enough time to reach a stable situation, i.e., two external events are assumed never to occur so close in time that the system does not have time to reach a stable situation.

Each transition has a receptivity. A receptivity may either be a logical condition, an event, or an event and a condition. In Figure 10 (left) three transitions and their receptivities are shown. The receptivity of the first transition is an event, $\uparrow x$. The receptivity of the second transition is a condition, y, and the receptivity of the last transition is a combination of a condition and an event, $x * \uparrow z$.

In the same Figure (right) an example is given of the events and conditions and the corresponding activation and deactivation of the two steps x1 and x2.

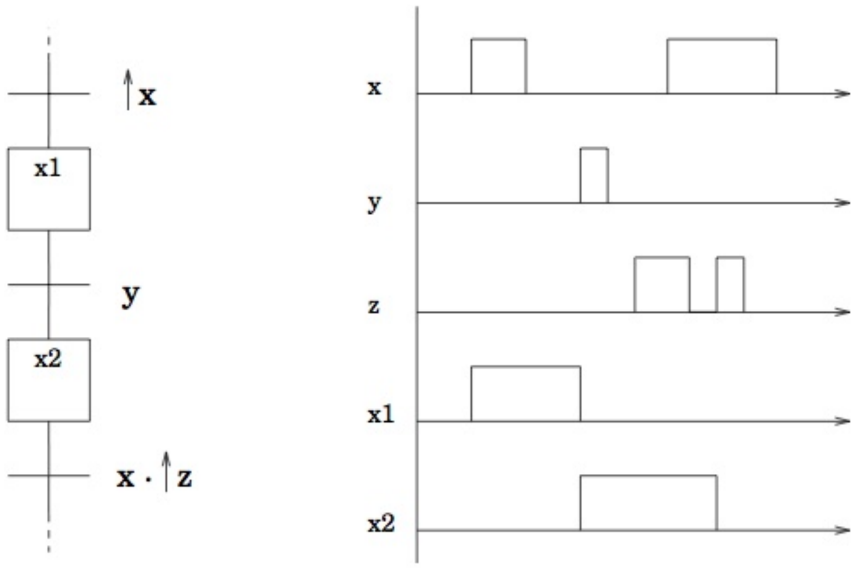


Figure 10: Three transitions and their receptivities

To facilitate the description of large and complex systems macro steps can be used. A macro step is a step with an internal representation that facilitates the graphical representation and makes it possible to detail certain parts separately. A macro step has one input and one output step. When the transition preceding the macro step fires the input step of the macro step is activated. The transition succeeding the macro step does not become enabled until the execution of the macro step reaches its output step. The macro step concept is shown in Figure 11.

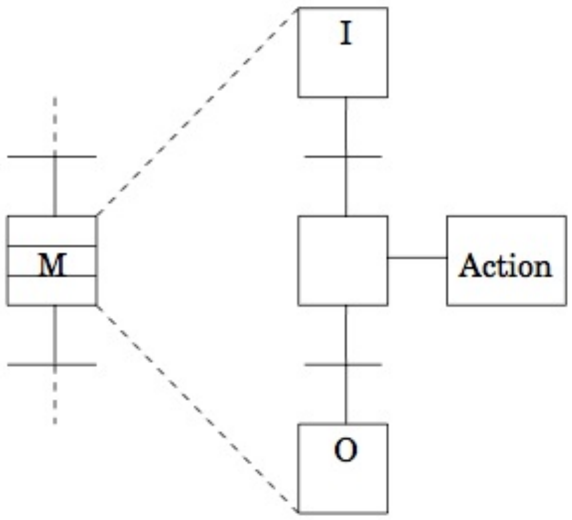


Figure 11: A macro step.

The dynamic behavior of Grafcet is defined by five rules:

1. The initial situation of a Grafcet is determined by its initial steps.
2. A transition is enabled if all of its previous steps are active. A enabled transition is fireable if its associated receptivity is true. A fireable transition is immediately fired.

3. Firing of a transition results in deactivation of its previous step and a simultaneous activation of its following steps.
4. Simultaneously fireable transitions are simultaneously fired.
5. If an active step is to be simultaneously deactivated and activated it remains active.

The aim of Grafcet, or SFC, in the standards has gradually shifted from being a representation format for logical controllers towards being a graphical programming language for sequential control problems at the local level. One main advantage of Grafcet, or SFC, is its simple and intuitive graphical syntax. Today Grafcet is widely used and well accepted in industry.

JGrafchart

JGrafchart is a Grafcet/SFC editor and execution environment developed at the Department of Automatic Control, Lund University.

JGrafchart provides graphical representation and execution of operation sequences, procedures, and state machines. It integrates features from Grafcet in IEC 61131-3, and Statecharts with concepts from procedural and object-oriented programming. JGrafchart is implemented in Java/Swing and runs on all platforms that support Java. The tool combines an interactive graphical programming environment with a run-time engine for execution of JGrafchart function charts. JGrafchart can be used for all types of discrete-event based applications, e.g., logical control, operating procedure management, recipe-based batch control, and workflow modelling. The high generality of JGrafchart makes it applicable in a wide variety of process control and operator support situations.

JGrafchart supports the following language elements:

- workspace objects
- Steps
- initial steps
- transitions
- parallel splits and parallel joins
- macro steps
- exception transitions

In addition there is support for:

- digital inputs and digital outputs
- analog inputs and analog outputs
- socket inputs and socket outputs
- internal variables (real, boolean, string, and integer)
- action buttons and free text for comments.

Sequence diagrams are created interactively using drag-and-drop from a palette containing the different language elements. The sequence diagrams are stored on JGrafchart workspace objects, see Figure 12.

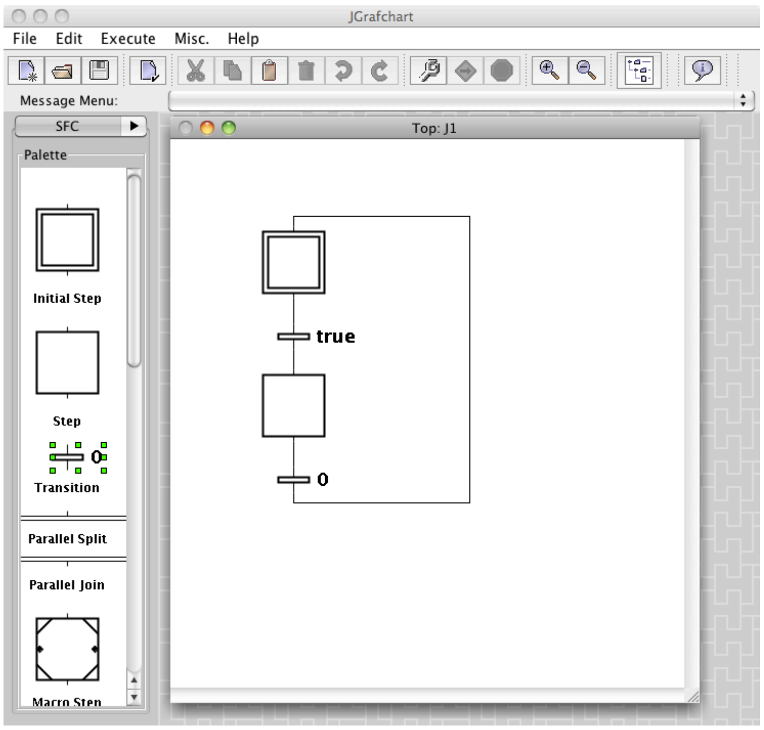


Figure 12: An example of a JGrafchart.

JGrafchart is presented in Laboratory Exercise 1.

Summary

In today's lecture the focus has been on Discrete Production Processes, see Figure 13.

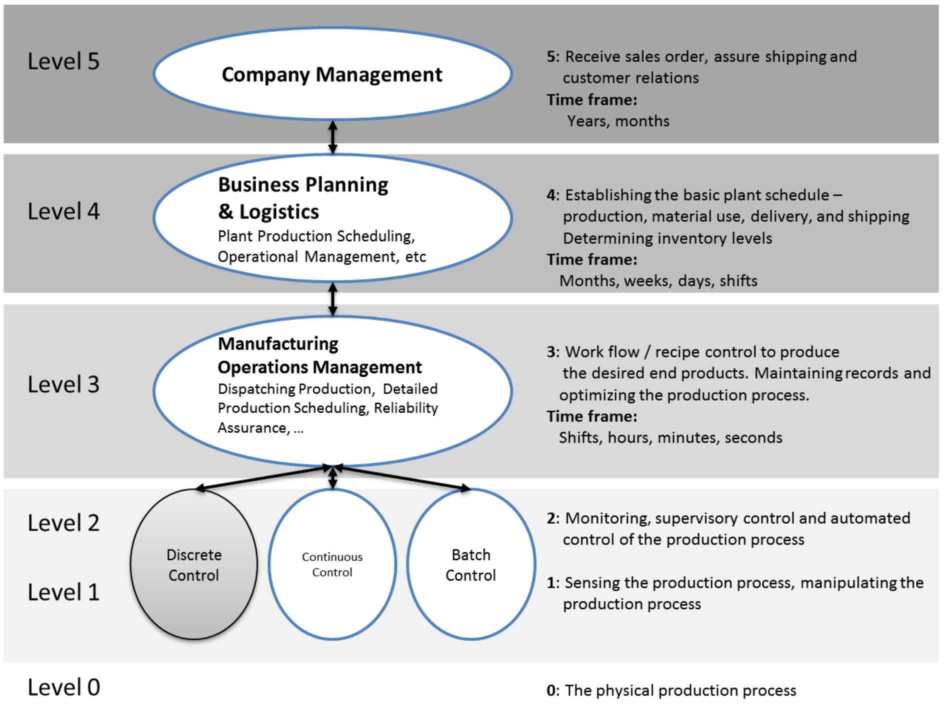

Level 5
Company Management
5: Receive sales order, assure shipping and customer relations
Time frame: Years, months
Level 4
Business Planning & Logistics
Plant Production Scheduling, Operational Management, etc
4: Establishing the basic plant schedule – production, material use, delivery, and shipping Determining inventory levels
Time frame: Months, weeks, days, shifts
Level 3
Manufacturing Operations Management
Dispatching Production, Detailed Production Scheduling, Reliability Assurance, ...
3: Work flow / recipe control to produce the desired end products. Maintaining records and optimizing the production process.
Time frame: Shifts, hours, minutes, seconds
Level 2
Level 1
Discrete Control
Continuous Control
Batch Control
2: Monitoring, supervisory control and automated control of the production process
1: Sensing the production process, manipulating the production process
Level 0
0: The physical production process

Figure 13: The discrete production process.

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