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Wrocław University of Technology

Production Management

Arkadiusz Kowalski

FORECASTING AND SIMULATION OF PRODUCTION PROCESSES

Wrocław 2011

Projekt współfinansowany ze środków Unii Europejskiej w ramach
Europejskiego Funduszu Społecznego

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Reviewer: Edward Chlebus

ISBN 978-83-62098-13-2

Published by PRINTPAP Łódź, www.printpap.pl

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1. Characteristics of modelled production processes

The most important task of production management is formulating the phenomena taking place in a production process in accordance with predetermined enterprise goals and with consideration of all conditions and circumstances under which real processes are being run [16]. Whatever the change is in a production system, it is preceded by appropriate production decisions. Production decisions are a key factor for further prosperity of a production company. Due to the production processes' character, decisions are always being made under conditions of risk and uncertainty. Additionally, bearing in mind production processes' complexity and their interconnections with other enterprise's areas and with the surrounding, the production decision making process ought to be preceded by production system analysis and risk assessment of launching a production. In order for the system analysis and risk assessment to be conducted swiftly, without interfering with the production course and realisation, simulation models construction appears indispensable.

One of the most fundamental problems in production systems analysis is their decomposition into constituents [16]. That decomposition should be dependent on goals, with which the decision maker is faced in the managing process [47]. High complexity and hierarchical process structure causes problems with determining the relevant levels and their number, for which an analysis would be conducted. Administering a research entails the necessity of collecting data originating repeatedly from various enterprise areas. In order to do so, many indicators are being garnered and scrutinised, which describe a given production system. Because of that, increasingly frequently production systems simulation models are being built, and when choosing a decision's variant, information tools such as integrated information systems and simulation programs are being used [47].

1.1. Type definition and ways of decomposing production processes

A production process is referred to as “an orderly set of actions (operations, activities) intended to produce an outcome (in form of a product or a service)” [55], [58]. A production process is running in a production system environment, i.e. an enterprise [16]. A production system is “a set of interconnected material, energetic, personnel, capital and informational resources. It is purposely designed and organised in such a manner, to be capable of satisfying clients’ needs” [16], [58]. A production system cannot exist without a surrounding, from which resources originate and in which profits required for further operation are generated [29]. This surrounding changes and affects the production system and conversely.

Depending on the character of material streams dominating in a given production are distinguished:

- Continuous production systems, based on constant technological processes, they can be found in e.g. energetic or chemical industry,
- Non-continuous production systems (so called discrete production systems), based on discrete technological processes, typical for the electromechanical industry including the automotive, machine building or household appliances industries.

In current industrial practice continuous processes, related to processing homogenous or closely homogenous material streams, fluids, gases, loose bodies or their mixtures, are automated to a great extent. Non-continuous production systems, processing streams of heterogeneous materials, related to machining, plastic working, welding and assembling, are automated to a lesser extent and in that area changes which have been taking place for the past few years are observed, which have a strong influence on present and future face of the industry [20]. Those changes are supported by conjoined development of new methods and means of production, where possibilities of modern computer techniques are utilised. On the other hand, to developing computer aided production systems are contributing – apart from the current computer technology development state – new methods of mathematical programming, modelling and computer simulation as well as increasing development of technology, managing methods and production organising.

Chosen and aforementioned above definitions and production systems types are not entirely conveying their specifics. Due to their complexity there is no physical possibility to present their specifics and constituents in single definitions or diagrams, and their decomposition should be dependent on the scope and area of conducted research and on assumed interval classifiers [64]. Chosen production system decomposition concepts are shown in the figure 1.

Decomposition 1 is dividing processes according to their relation with the manufactured product. Fundamental production processes are directly, realising basic goals or production system tasks in form of products passed on to the system surrounding. Auxiliary processes are servicing all processes in a production system, reinforcing them with their products, services or information. The effect of their realisation is existence of a feedback net between the system and its surrounding [16]. Decomposition 2 assumes production system division into system input subsystem, processing subsystem and system output subsystem.

Next decomposition assumes production system division into processes according to particular types of production operations, i.e. sets of activities aimed at transforming input materials into ready-made products [55].

Correspondingly to phenomena taking place in a production system, production operations can adopt a form of: technological, transport, control, storing and maintenance. A set of technological operations constitutes a technological process, a set of transport operations constitutes a transport process and a set of control, maintenance and storing operations constitutes processes of control, maintaining and storing accordingly.

A production system can be divided into processes, correspondingly to the place they take place in, into external processes – being conducted outside an enterprise and internal – being conducted within an enterprise. Should one want to analyse a production system structure, one would need to decompose it into individual production cells, but also, despite it not being shown in figure 1, into work cells, organisation cells and departments, individual products and so on. A production system can also be scrutinised from the perspective of management and production phases.

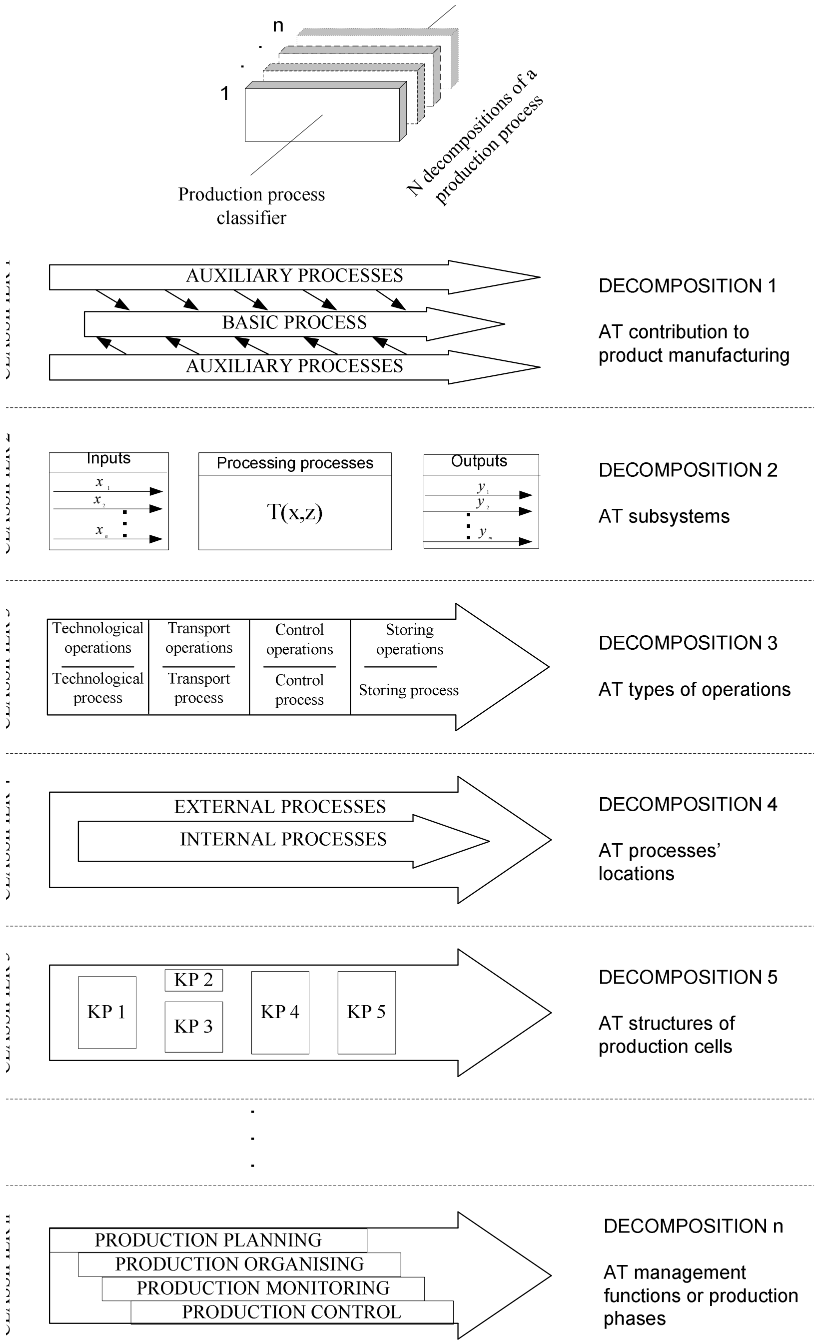


Fig. 1. Cross-sectional decomposition of the production system at the selected classifiers [16]

Presented in figure 1 and above discussed classifications, do not deplete classification possibilities and production processes division, however they reflect the most frequently encountered in literature classifications [16], [30], [31], [55], [58]. A way of decomposing should be dependent on the goal appointed to production system analysis, in order for the decision made on that ground to be optimum and burdened with the minimum risk possible.

1.2. Elements of a production system and process

When conducting a production system analysis, apart from an appropriate decomposition, choice of elements subject to scrutiny is equally important. Six vital elements can be listed, which are deciding about the structure and features of realised production processes. They are the following [25]:

- Enterprise organisational structure,
- Production and logistics control rules,
- Technologies,
- Techniques and methods of product and production processes development,
- Rules for planning and selecting production systems,
- Machines and production devices.

Those elements can adopt a form of a diverse range of technical, organisational means, techniques, methods and even phenomena [25]. Above-mentioned elements and their most significant constituents are schematically depicted in figure 2.

On production process specifics, apart from the aforementioned elements, particular parameters have got an influence. Because a production process runs through an entire enterprise, the describing it data originate in many areas. Production process describing parameters are infinite, as well as ways of its decomposition. The choice of suitable parameters in a process analysis should be dependent on a decision problem. Highly simplified parameters structure describing a production system is presented in figure 3.

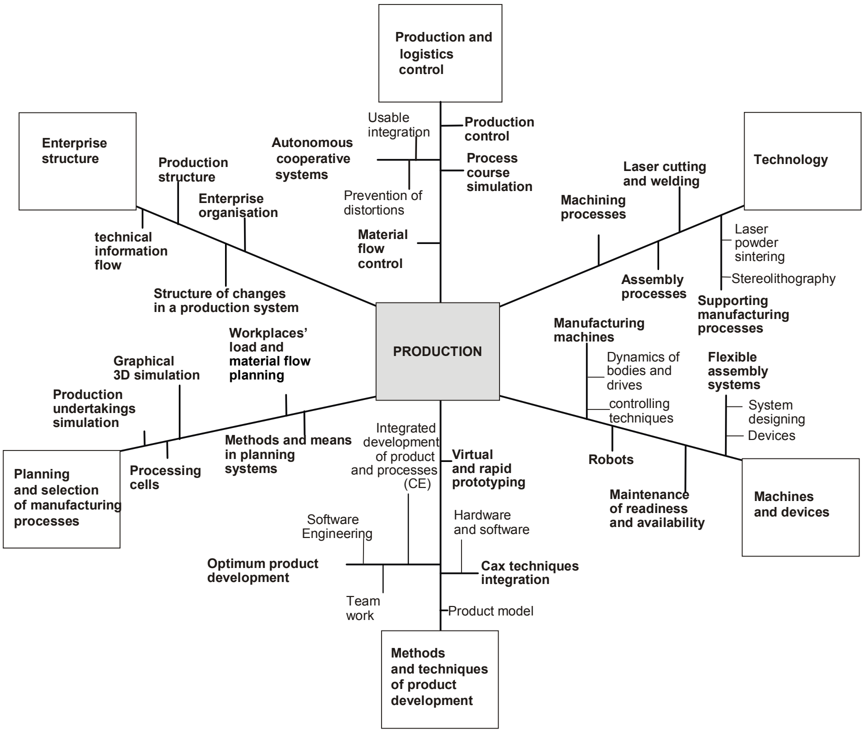


Fig. 2. Main elements and their constituents describing production process [25]

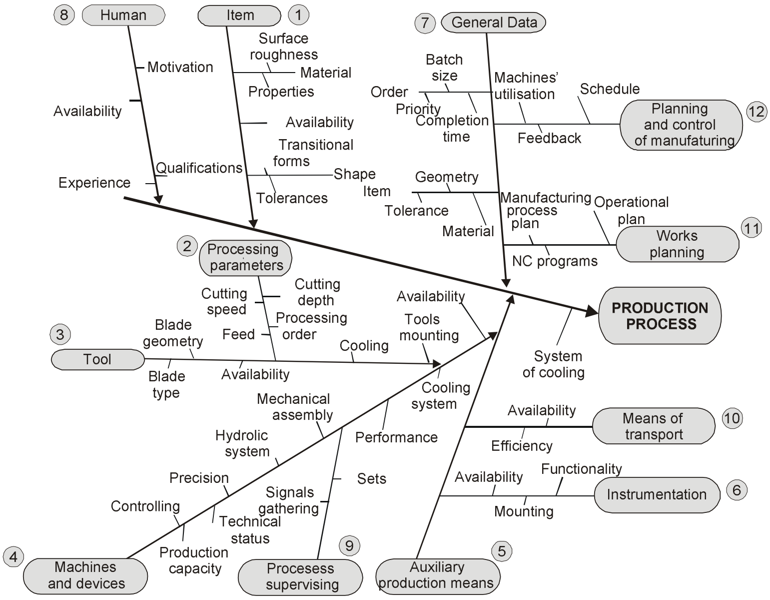


Fig. 3. Structure of basic parameters of a production process [25]

Hierarchical representation of parameter structures of a production process shows also interconnections of specific enterprise areas and the process's functions and parameters.

1.3. Planning and forms of production batch running

Production process comprises all activities requisite for manufacturing certain products. Those processes are: semi-finished products manufacturing, individual parts processing, assembly, quality control, transport, storing, maintenance and etc. The fundamental part of a production process, directly related to alteration of shape, dimensions, surface quality and physicochemical properties of a processed item is *technological process* [32].

Series production is characterised by the fact that products are manufactured in series and batches in specified time intervals. The term production batch is used to describe a number of items being processed at a workstation while each operation's completion, without a pause for another production. By the series term one should understand in turn, that it is a number of simultaneously assembled products. Depending on series volume, processing laboriousness and the frequency of its repeating, series production can be divided into:

- Low-volume,
- Medium-volume,
- Large-volume.

Basic production traits are the following [14]:

- Straining individual workplaces with periodically repeated operations,
- Apart from universal machine tools, using specialised machine tools, adapted to perform particular operations,
- Utilising in a broad scope handles, instruments and special tools, hence bringing marking out down to a minimum,
- Decreasing the number of highly qualified staff (compared to unitary manufacturing),
- More detailed technological processes elaboration than for unitary manufacturing,
- Workplaces distribution partly according to kinds and partly according to the order of performed operations, in effect of which so called machining cells are created (objective).

Machining cell is a set of workplaces intended for making different parts of similar technological processes. In comparison with the arrangement by kind we gain at inter-operational transport and the possibility of employing low qualified blue collar workers.

During the technological process elaboration intended for series production the *optimal batch size* needs to be determined. Batch size has got a substantial effect on the technological process, because the smaller the transportation batch the simpler means of production should be used. Increasing the number of units in a batch or a set causes some of them to wait redundantly in storage before proceeding onto the next operation.

That results in considerable extension of product manufacturing cycle, so the time from the batch (set) processing commencement of a product right up to the finalisation of the final assembly. It affects negatively economic results of a company, because of freezing large financial resources in production. A conclusion can be drawn that the optimum batch size should be determined in such a way, that the sum of losses for tooling time and means of production engagement should be the smallest. The most common formula for determining the optimum size is [51]:

$$n = \frac{Nf}{F} \qquad (1)$$

where:

n – number of units in a batch,
N – number of units according to annual production program,
f – reserve of parts assembly-ready (in working days),
F – number of working days in a year.

By product manufacturing process planning we understand determination of the way processed items are passed between workplaces. On the way products or details are passed the production cycle's length is dependent, along with machine and device utilisation degree, work-in-progress reserves amount, level of circulating assets engaged in production and so on, what in significant manner influences the production costs value.

The time of operation upon a single unit, that is normalised operation time, is being corrected only against real conditions and amounts to [55]:

$$t = \frac{t_j}{\varphi} \qquad (2)$$

where:

t – time of normalised operation,
t_j – operation time per unit,
φ – normalising coefficient.

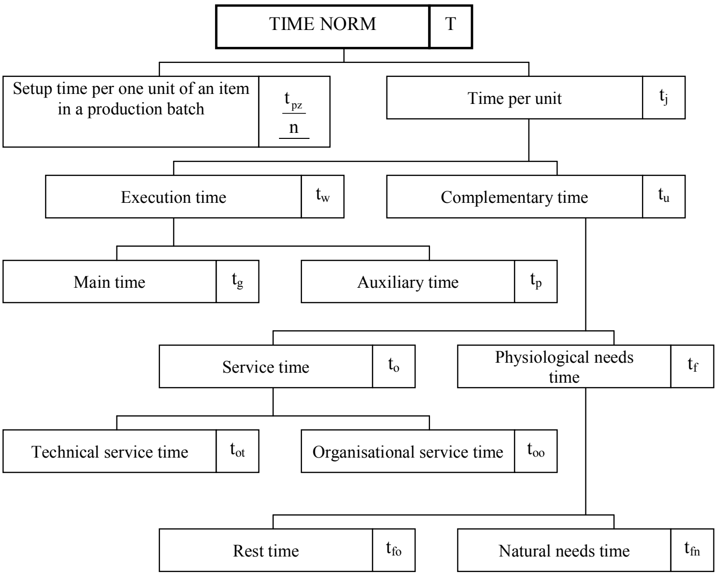
Cycle time t_j is determined experimentally or computationally, it can be found on the time normalising chart. It is composed of execution time and complementary time i.e. service time and physiological needs time. The need for a station's rearming occurs in unitary and series production. Under conditions of serial production, where a single workplace performs constantly a predetermined operation, stations do not require tooling times.

In order to describe the course of a technological operation in units of time, time norms are used, depicted in figure 4.

Three ways of production running are differentiated by workplaces [17]:

- serial,
- parallel,
- serial-parallel.

Serial production course means, that every subsequent technological operation is initiated only after completing the preceding operation upon all products or details, constituting a given production series.



n – number of units in a production batch

Fig. 4. Diagram of time norm construction [68], [58]

From a single workplace to another an entire batch of processed products is transported – figure 5.

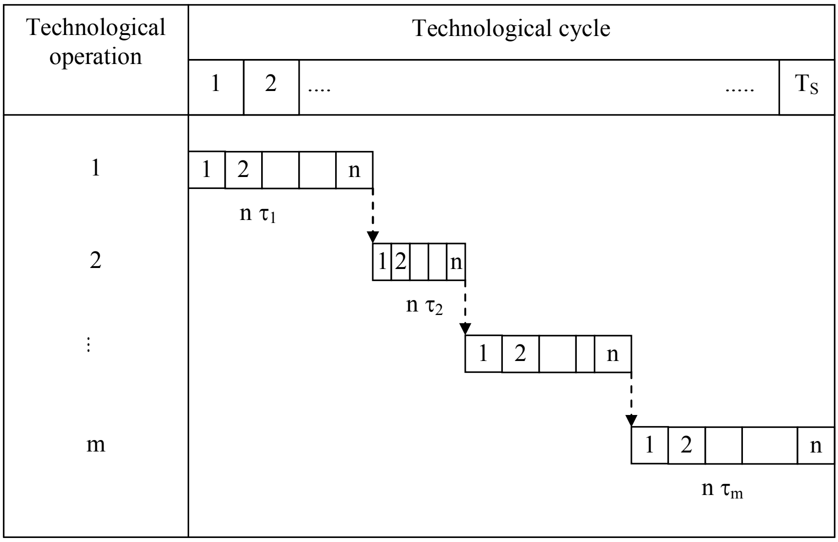


Fig. 5. Diagram of serial production course [52]

In serial production course the length of a technological cycle equals the sum of duration times of technological operations being realised upon an entire products batch. Product manufacturing using serial production running extends production process time. It is a result of detaining already processed products within a workplace, until a given technological operation is performed upon the entire batch.

$$T_S = p\sum_{i=1}^{m} t_j \tag{3}$$

where:

T_S – complete time of a production batch processing,
t_j – cycle time of processing a single element,
p – number of elements in a production series,
m – number of technological operations.

Serial course of the production process is used in unitary production and low-volume production, it is particularly advantageous when we deal with:

- short production series,
- low number of technological operations,

- small size stocks of machines,
- low material intensity [69].

Parallel production course characterises with individual products being passed onto the next station instantly after completing the preceding technological operation. In this system individual, being processed units are passed between workplaces, independently of the time a technological operation lasts (figure 6).

When synchronicity is lacking, that is when individual operation times are not equal across the board, in workplaces executing operations shorter than t_{max} breaks in work are going to take place. During parallel running, part of production batch is simultaneously under the process of technological processing. It causes substantial production cycle shortening, particularly big when compared with serial production course.

Technological cycle length during parallel production course is equal to the sum of individual technological operations running times referring to a single product, enlarged with the product of longest lasting operation time and the number of processed items reduced by one.

$$T_R = n \cdot \sum_{i=1}^{m} t_i + (n-1)\max_i t_i \tag{4}$$

where:

T_R – technological cycle length,

n – number of processed items.

Within the framework of the parallel production course, processed items are passed on also in transportation batches of p units. The formula becomes:

$$T_R = n \cdot \sum_{i=1}^{m} t_i + (n-p)\max_i t_i \tag{5}$$

where:

p – number of units in a transportation batch.

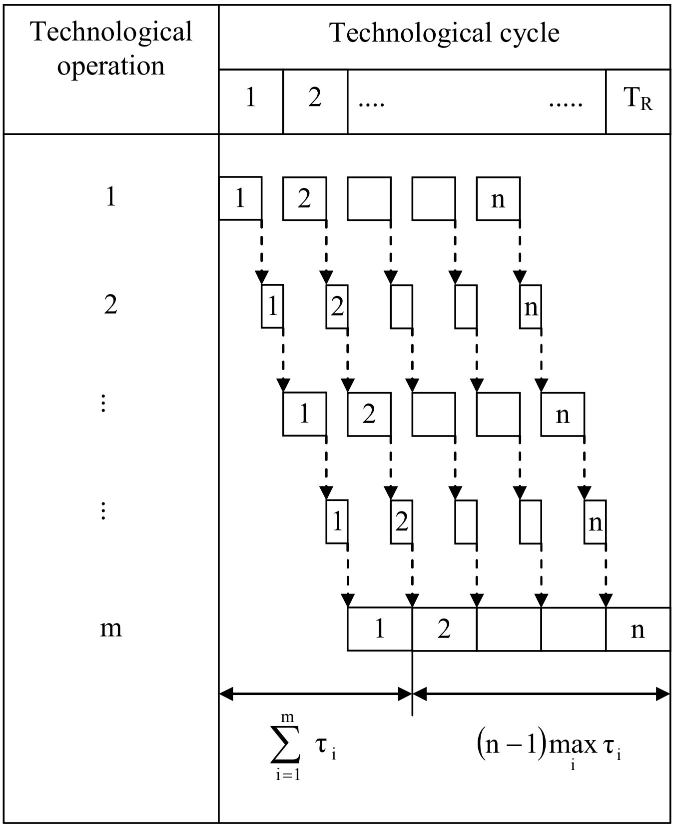


Fig. 6. Diagram of parallel production course [52]

Parallel production course has got drawbacks also – passing of individual elements from workplace to workplace requires increased frequency of transportation passes. This system should be used in case of objective workplace distribution, particularly for production lines. Large benefits are being achieved for:

- long production series,
- extended lengths of time of technological operations with their low time differentiation for ensuing processing phases.

Serial-parallel production course constitutes the connection of serial and parallel elements of passing on processed items from operation to operation. Individual products or elements are packed either individually or in transportation batches (figure 7).

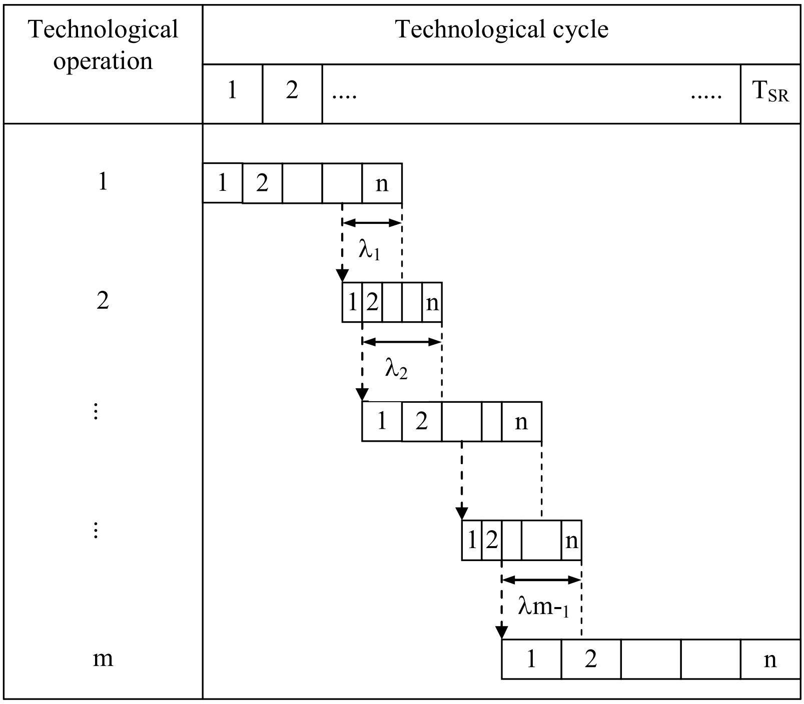


Fig. 7. Diagram of serial-parallel production course [52]

The way of transporting is contingent on consecutive technological operations' lengths of time. Two situations are possible:

- time of preceding operation τ_i is shorter than time of the subsequent operation τ_i+1 or is equal ($\tau_i+1 \geq \tau_i$),
- time of preceding operation τ_i is longer than time of the subsequent operation τ_i+1 ($\tau_i > \tau_i+1$).

In case of the first condition, processed items are moved individually from operation to operation, in order to commence longest lasting technological operations as soon as possible, thus decreasing the production cycle length. In practice passing on elements in batches is also commonly met.

The second condition means moving processed items between stations determined by transportation batches. Execution of shorter lasting technological operation in batches requires an earlier accumulation of processed items next to the passing stations.

Technological cycle length during serial-parallel production course T_{SP} equals technological cycle length during serial production course T_S decreased by time, in which the work of every two consecutive workplaces (*i* and *i+1*) is overlapping.

$$T_{SR} = T_S - \sum_{i=1}^{m-1} \lambda_i \tag{6}$$

By substituting the expression T_S with the equation 1 and assuming $\lambda_i = (n-1)\min(\tau_i, \tau_{i+1})$, where i = 1, 2, ..., m–1 the formula is presented as the following:

$$T_{SR} = n\sum_{i=1}^{m} \tau_i - (n-1)\sum_{i=1}^{m-1} \min(\tau_i, \tau_{i+1}) \tag{7}$$

When passing on of processed items is taking place in transportation batches p items each, the formula for technological cycle length during serial-parallel production course adopts the form for $\lambda_i = (n-p)\min(\tau_i, \tau_{i+1})$, where i = 1, 2, ..., m–1:

$$T_{SR} = n\sum_{i=1}^{m} \tau_i - (n-p)\sum_{i=1}^{m-1} \min(\tau_i, \tau_{i+1}) \tag{8}$$

The presented system of production course finds application during series production, especially when the following are taking place:

- long production series,
- extended lengths of time of technological operations, with high differentiation within the framework of following processing phases.

When making a choice between production courses for a production program, one should be guided by the degree of machines and human resources utilisation.

An important issue is modelling of a product manufacturing process course in order to rationally shape technological processes. Irregular character of those type processes' courses doesn't allow for using traditional, based on experience and intuition planning methods.

2. Modelling and simulation, theoretical basis

2.1. System, modelling and simulation

System is defined as a set of entities, e.g. people, machines, which are acting and affecting each other in order to achieve some logical outcome (a definition proposed by Schmidt and Taylor, 1970).

Real system is part of the real world. System can be either artificial or natural, currently existent or planned for the future. System perception is dependent on goals of conducted research. A set of entities, which are creating in a given instance certain system, can only by a subsystem during an analysis of a different system.

From a systematic point of view a model, in a synthetic take according to needs of: description, research, constituting, development and using, should facilitate:

- representation of fundamental system traits,
- presenting system development possibilities,
- decision formulation,
- appraisal of effectiveness and destructibility of a system,

and reproduce:

- structural relations within a system crucial due to functionality,
- fundamental functional relations within a system [50].

System complexity is mainly a function of the following two factors:

- interdependencies,
- variability.

Dependencies are causing the behaviour of a single element to influence another element in the system. It takes place, when a resource is allocated to one or more actions (activities). The complexity is more dependent on the number of relations between elements, than on the number of elements within the system. Elements strictly connected with each other have got greater influence on the system that elements loosely related. Impact of loosely connected elements on the system is often delayed. Cause and effect are set apart from each other in time and space. The best way to deal with dependencies is to eliminate them. Unfortunately it's not entirely possible, because it clashes with a system idea, which is the synergy effect achievement. This effect cannot be attained though, if system elements were to operate in isolation. Dependencies eliminating techniques are leading to reserves surplus and incomplete resources utilisation.

Variability is deepened by already existing, unpredictable independency effect causing the system to become even more complex. Ignoring variability leads to the system traits' disfigurement and consequently to imprecise reality reproduction. Table 1 shows exemplary system elements eligible for variability. Variability should be reduced by all available means, and even eliminated where it's possible, because system planning becomes easier then.

Table 1. Examples of variation in a system [40]

Type of variation	Example
Time of activity	Processing time, repair time, setup times
Decisions	Rejection or acceptance of a part
Quantity	Batch size, number of absent employees
Time between events	Time between commodity deliveries
Attributes	Preferences of clients, skill level

Modelling means an action of selecting a suitable substitute for an original called model, so it is a rough recreation of the most important original's properties. The very fundamental goal of modelling is simplifying complex reality, facilitating its submitting for a research process.

Thanks to modelling:

- research subject can be decreased or increased freely to any size,
- processes difficult to capture due to their too brisk or too sluggish pace of running can be analysed,
- one chosen, isolated aspect of an issue can be examined, avoiding other [28].

Process cognition and proper – if needed – expression of results of that cognition, in form of process models, constitutes a crucial factor of correct actions in different life areas.

By process modelling we call approximate process reproduction. Process models creation is intellectual reality recreation or certain relations to realities referred to, and experimental research. Process modelling is subject to the following rules:

- compliance with nature and in consequence with forces of nature,
- inferential resulting, i.e. compliant with rules of logic,

- conformity in form of expression, usually mathematical form, with the aforementioned rules,
- systematic process modelling, in other words partial action relativity in the context of a whole [28].

There are two main reasons for processes modelling. The supreme first one being processes cognition. The second, is the need for resolving practical issues. Cognition is a sufficient reason for processes modelling. However the second reason is connected to social needs satisfying. Thanks to processes cognition practical problems can be solved [28]. In industrial practice a certain groups of issues exist, which demand direct assessment of complex system actions, which are taking place in conditions of uncertainty or possibility of choosing an alternative solution. Those issues in current conditions are being resolved be means of computer simulation of virtually created production processes or systems. Computer simulation in the range of production processes designing may concern issues recognised as "macro" scale, referring to manufacturing or analysing machine processes controlling work of self-reliant, autonomous machines – or in "macro" scale – within the scope of design and operational analysis of work in cells or production lines [44].

Due to the substance of activities aimed at decision making, or determining unknown features or production system parameters, two kinds of design tasks can be distinguished:

- type analysis task,
- type synthesis task.

Type **analysis** tasks are used mainly in order to verify solution variants, at different stages of production system designing and different steps of production controlling (figure 8). Type synthesis tasks are usually formulated and solved in order to generate solution variants, e.g. production plan determination (figure 9).

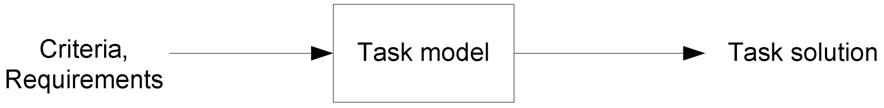


Fig. 8. Type synthesis task [55]

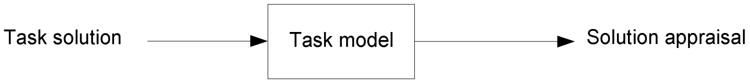


Fig. 9. Type analysis task [55]

While designing and analysing production systems, there is a necessity of making many design decisions. Large number of possible variants and their complexity often renders impossible to choose an optimum solution by means of classic tools, whereas such possibility is given by simulation methods.

The following actions in process modelling can be distinguished – figure 10.

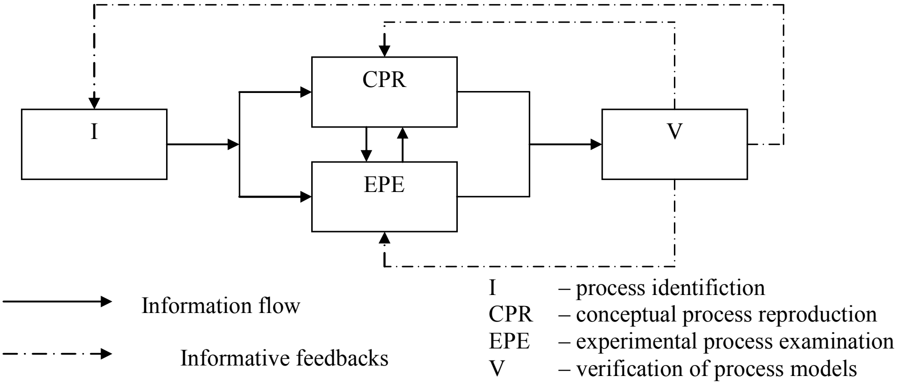


Fig. 10. General diagram of process modelling [28]

As first process identification is taking place concurrently the following can be conducted: intellectual process reproduction and experimental process analysis, after those activities process models verification takes place.

For systemising diverse range of models different criteria are used – figure 11. For the production management's point of view a useful classification is one which takes into account so called model substantiality – figure 12. From that point of view the following models can be listed:

- abstract, so informational
- concrete, so energy-material,
- energetic, so energy-material-informational-time

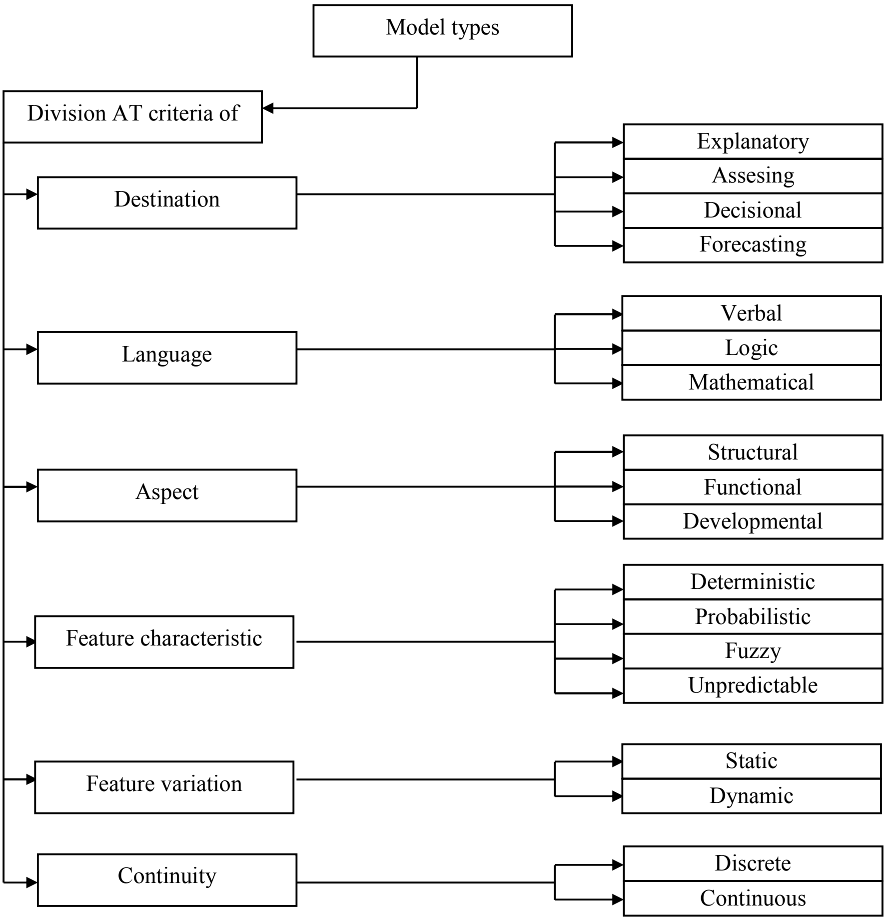


Fig. 11. General model specification [50]

Those models, being generators of modelled systems' state differ substantially from abstract models and concrete models with energy-material factor as well as informational-time factor.

The term *computer model* means associated with a computer of certain configuration (*hardware*, energy-material part) simulation program (*software*, informational part). More often such model is called *simulative*, however it is not entirely an accurate term. It can be agreed on for common use owing to the fact, that other types of simulations without a computer are currently marginally used. In the subsequent part of the research, problems connected with the issue of creating and applying energetic simulation models are dealt with.

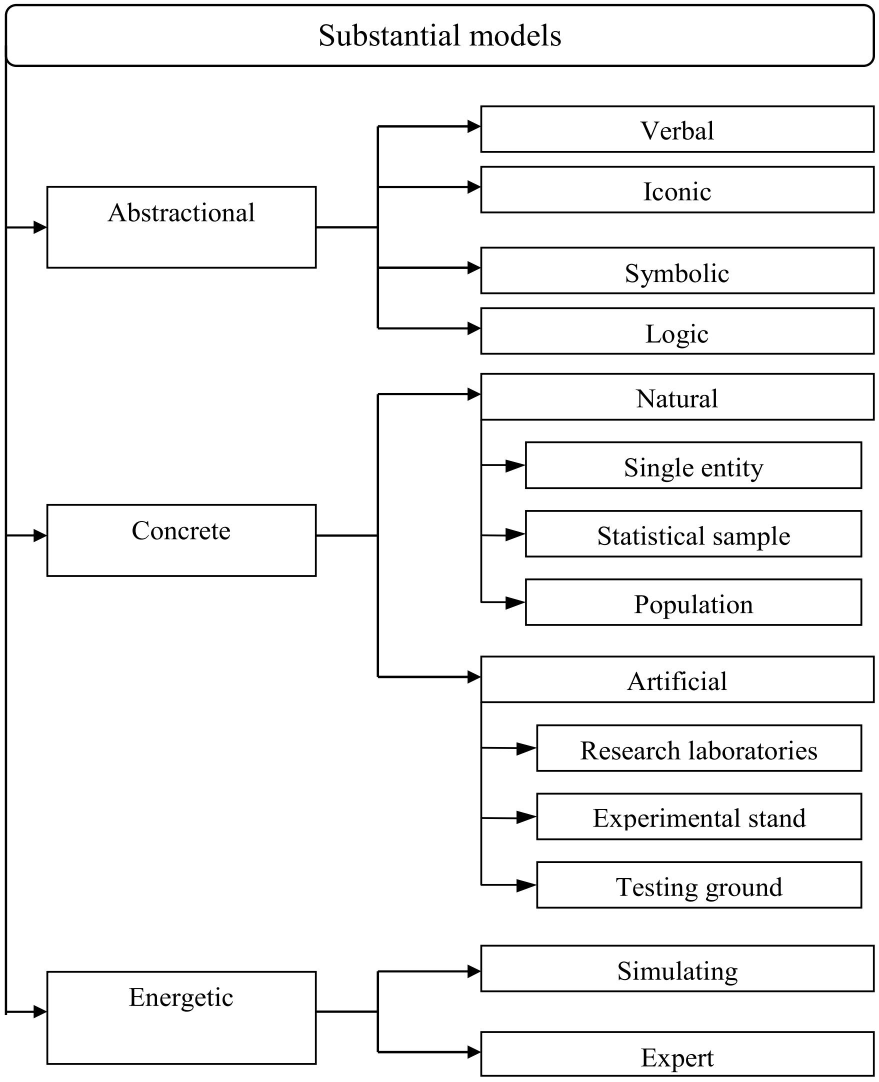


Fig. 12. Model division AT to their substantiality [50]

Energetic models are constituting in production management a class of models, which is not considered in conventional specifications. That model group includes:

- computer models called simulative,
- expert models.

The essence of a simulation model boils down to the transformation of an algorithmic model into an information form. The sequence of actions and the final form of the model are dependent on the model class, modelling goal, existing possibilities in terms of access to software and hardware information means [50].

Modelling and simulation are a set of actions related to building real systems' models and simulating them by means of a computer. It results from the definition, that three major element can be distinguished – real system, model and computer. Dealing with modelling and simulation, one not only encounters along the way different elements, but also relations between them. In particular, modelling concerns primarily dependencies between real systems and models, and simulation is related mainly to dependencies between computers and models. Hence the subject matter is characterised by three elements and two relations – modelling relation and simulation relation [75]. Those dependencies are shown in figure 13. Real system is a part of interesting to us real world. System can be either artificial or natural, currently existent or planned for the future. One could say, that a real system is a source of information. A model then, is going to be a set of instructions for generating data of reaction. Computer provides calculations computing, given appropriately coded model instructions are fed to it. In such way, data about a reaction are going to be generated. Modelling relations, regards model's validity, revealing how good a model represents a real system.

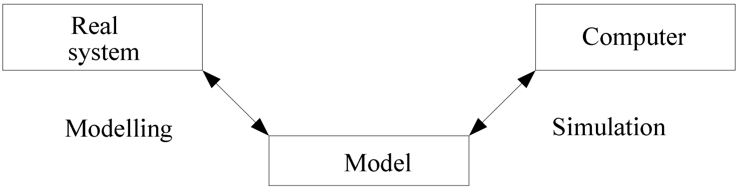


Fig. 13. Fundamental elements and relations of modelling and simulation [75]

Simulation's relation considers the fidelity with which computer executes instructions demanded by the model. Fidelity with which a program realises a model is often related to the program's correctness [40].

Currently modelling and simulation have to be mentioned in the same breath. Those notions are usually used together and are mutually overlapping. Chiefly a model is created with a particular aim in mind: to analyse the system and optimise it. In order to do so, not only a model needs to be built, but also a need exists of running a simulation.

According to VDI–Richtlinie 3633 simulation is "*creating a research environment imitating a system with all its dynamic* *processes described within the model, out of which obtained research results are representative (transferable) into the real world*" [33].

Particularly significant meaning is assigned to the advantages of simulative research methods in the area of planning and designing production systems and processes, especially in phase of their development for new production tasks. Four fundamental levels of simulative research can be distinguished: enterprise, production department and workshop, production cell and functional fragments of the aforementioned areas of an enterprise. It is mainly crucial during elaborating new products and their production processes and entire production undertakings. Simulation methods and tools are allowing for finding optimum organisational structures and parameters of production process realisations already on the stage of drawing them up.

From amongst numerous available definitions of simulation and computer simulation were chosen ones, which represent different takes on the subject:

„An attempt to describe the interrelationships among a corporation's financial, marketing, and production activities in terms of a set of mathematical and logical relationships which are programmed into the computer." (Naylor, 1966)

„*Computer simulation is a process of designing a mathematically-logical real system's model and experimenting upon that model be means of a computer.*" (Pritsker, 1986)

„*Computer simulation is a method, which can be used for a real system's state analysis*" (Anderson, 1991)

„*Computer simulation is a discipline of model designing on the basis of a real system by using computer and results analysis*" (Fishwick, 1995)

„*Simulation is an art and a science of creating presentations of a process or a system in order to conduct experiments and assessments*" (Gogg and Mott, 1996)

„Simulation is a wide set of methods and programs for imitating behaviour of a real system, usually by means of a computer, by applying relevant software." (Kelton, Sadowski & Sadowski, 1998)

Understanding simulation facilitates its proper application and assessment of its results. In order to obtain maximum benefits from modelling and simulation their basic technical issues need to be understood.

In simulation software the following three simulation types are applied:

- static and dynamic,
- stochastic and deterministic,
- discrete and continuous.

Static simulation model is such a model, where time alteration has got no effect on the experiment's outcome, so passing of hours, minutes, seconds doesn't play any role. Good example is a simulation model describing a roll of dice, where obtained results are completely independent of time. An example of simulation methods for static models is the Mote Carlo method. That method is used for mathematical modelling of complex processes. An important part in this method is played by drawing (random selection) of values characterising a process, however the drawing applies to known distributions.

Dynamic simulation models are models, which are heavily influenced by lapse of time. The state of a model changes gradually with time.

Static vs. dynamic simulation

Static simulation is not based on time. Data for simulation is often gathered by statistical research. Monte Carlo method is used for mathematical complex processes (integrals computing, statistical processes chains), in order to allow for their results predicting using an analytic approach. An important part in this method is played by drawing (random choice) of values characterising a process, however drawing applies to known distributions. Dynamic simulation describes changing in time behaviour of a modelled system [76].

Stochastic vs. deterministic simulation

Stochastic simulation is based on stochastic processes, meaning they were built out of random sequences from generated values. Periods of time between moments, when a machine is breaking down, or times needed for its repairing are examples of stochastic processes. Values (e.g. times) change in a random manner and require application of methods from the area of probability theory. *Stochastic* simulation refers to a simulation, where one or more input variables are random. Stochastic simulation generates a result, which on its own is random – figure 14.

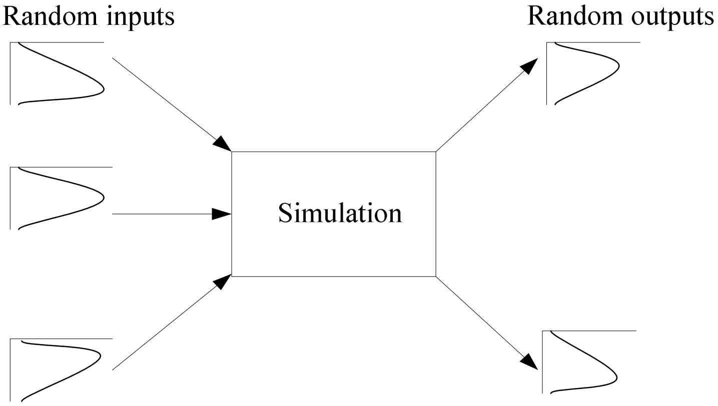


Fig. 14. Example of a stochastic simulation [40]

Deterministic simulation models are such models, where no random events are used. It means, that the course of a simulation experiment is not subject to probability. Models in deterministic simulation are built similarly to stochastic models, apart from the randomness. In deterministic simulation all future states are predetermined, in a situation where input data are defined. As shown in figure 15, deterministic simulation has got predictable entries and gives predictable results. Stochastic simulation has got random entries and gives random results. Deterministic simulation is going to always yield exactly the same outcome, regardless of number of times it is run. In stochastic simulation several random tests need to be carried out, in order to conduct a correct results appraisal, because each test differs statistically.

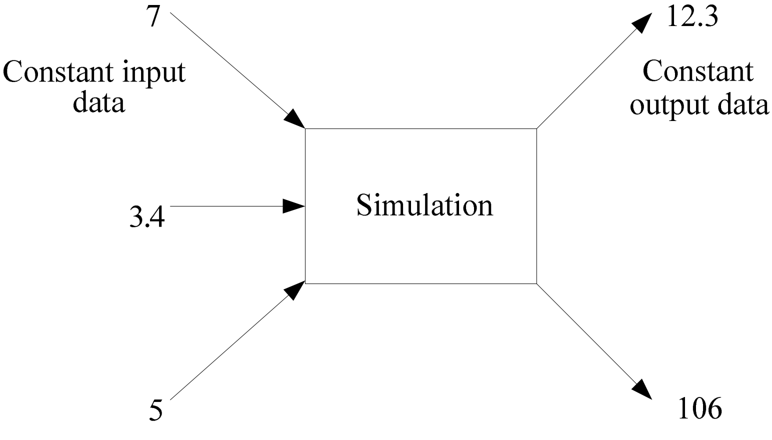


Fig. 15. Example of a deterministic simulation [40]

Discrete vs. continuous simulation

Discrete simulation is a simulation, where changes are occurring in fixed time points. Changes in the model are taking place in the moment of certain events appearance – figure 16. Majority of production systems is modelled by means of discrete simulation.

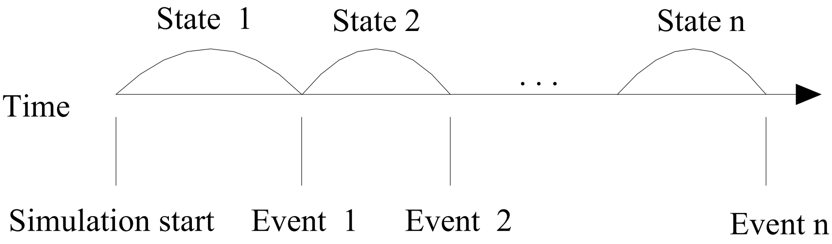


Fig. 16. An example of changes in a discrete simulation [40]

In continuous simulation changes are taking place constantly in the context of time. A simulation is continuous, if values assumed by description variables can be represented by real numbers or their intervals [40]. Continuous models are described by a differential equation. In practise, it is difficult to find a system, whose events would have been completely continuous across the board, or completely discrete, but usually it is possible to recognise, which of characteristics (continuous or discrete) dominates is an analysed system.

2.2. Simulation modelling

First information about using simulation clocks back to antiquity [19]. Those were the beginnings of simulation games, intended to train:

- military commanding officers (e.g. Pyrrus's simulations [319-272 BC] and Filopojmen's [253-183 BC]),
- lawyers (judicial practice of Roman lawyers and Controversiae rhetorical training),
- future rulers (e.g. a game originating from 567 year BC recreating ruling over Medes' country).

In more recent times simulation games systems were emerging more and more frequently:

- tactical and operational games of de Guiberts from years 1753-57 (France),

- operational and strategic games of Anthony Leopold Oelsnitz initiated in 1769 in Corps of Cadets (School of Knights) in Warsaw,
- fortification game of de Cormontaigne (1741) – strongholds' defending capabilities analysis,
- McCARTY (1889) – sea war games taking place in US Naval War College Newport,
- Von MANSTEIN (1929) – planning game for analyzing the aftermath of Poland's attack on Germany, played out in General Staff of Reichswehr.

One of pioneers of modern simulation was a Hungarian mathematician John von Neuman, who in the forties proposed use of random numbers (statistical data) for modelling a real system. That method was called Monte Carlo and was used during the II World War to solve problems related to construction of the nuclear weapon (amongst other a direct simulation of interpenetration of random neutrons in a fissionable material) or in the analysis of air raid's bombing effectiveness [18]. Those methods have also found their use in solving some integral equations [20]. Whereas in the industry, that method was used for determining a factory's maximum output.

The notion of system simulation was applied for the very first time at the beginning of the fifties, when scientific research started to analyse issues by concentrating on links between individual fragments. It was due to the emergence of possibilities of conducting simulation experiments by means of electronic digital machines, which also had gone through a certain development stage in terms of computing power (speed).

The very first simulation program was created in General Electric and was used for analysing production problems in facilities [18]. It was published at the international conference of Operations Research (Second International Conference on Operations Research). Whereas in commercial software, simulation had started to be used in the sixties. The very first models were programmed in the Fortran language and often consisted of many thousands of lines of code. Not only model construction was an arduous task, but also finding mistakes in the code proved tedious. It took a year or more to complete and unfortunately the obtained results of modelling were not provided in an adequate moment for the decision making process. It had used to be the case for the last few decades during which simulation had been gaining popularity as a tool aiding decision making in production industry and services.

Simulation allows for analysing a system's behaviour without the need of constructing the real system or conducting experiments on an already-existent real system. Hence it is being used, where there are no other ways of resolving a posed research problem (e.g. there is a lack of analytic solutions of a model in form of differential equations), or there are other ways of resolving a posed research problem, but due to criteria: economic (e.g. energy, effectiveness, cost), ethical or biological (e.g. safety) they were acknowledged as less attractive then the simulation method e.g. nuclear reaction, human brain examination and so on.

Currently simulation is used in numerous areas, predominantly as an educational technique facilitating development of peoples' appropriate reactions e.g. in military war games are utilised, for managers – managerial games; for people set to work in hazardous environment e.g. pilots, cosmonauts, scuba divers and so on, suitable simulators are employed. Similar application simulation has got in sport. There is a great deal of interest in simulation used for entertainment, examples here being computer and board games. Simulation is also used in: meteorology, demography, economics as well as technology.

Often, simulation is employed as a tool aiding decision making in production industry and services. First and foremost it is used in production systems, storehouses and distribution systems. Those systems have got clearly determined dependencies and procedures, which are easily transferable and applicable in simulation modelling. For example in construction works simulation is utilised for describing, visualising a system not yet existent in order to find an optimum construction solution. Production process models can then portray individual machines' performance, material preparation time beforehand of an operation, transportation time required for moving goods between machining stations, human factor and so on. Whereas in order to learn an existent (operating) system's behaviour and its production capacity, a model is built, based on data gathered from the real system. Such model can be used for a real system's optimisation.

During past few years computer simulation has gained substantial popularity thanks to:

- increase of simulation awareness and understanding,

- increase in availability, abilities and simulation programs' ease of use,
- software and computer hardware price falls.

2.3. Discrete processes simulation methods

Simulation methods are a broadly used notion, referring to modelling and analysis, numeric usually, processes' course and programs. We distinguish two main simulation methods: continuous simulation – called J.W. Foster method and discrete simulation. Differences between those two approaches are shown in table 2.

Table 2. Differences between continuous and discrete simulation

	Continuous simulation	**Discrete simulation**
Lapse of time reproduction method	Constant step concept. Lack of system's activity is taken into account (calculations without events). Processing in DT events, which are treated as simultaneous at the end of DT section. DT simulation step exists.	Subsequent events concept. Lack of system's activity is not taken into account (only events). Lack of processing events as simultaneous (exception, when event i = event j). Lack DT simulation step.
Modelling aspects		
Modelling subject	Flows	Dynamic objects and everything what happens with them
Flow sequence and rules	FIFO rules (first in first out)	FIFO rules, LIFO, priorities, randomness
Application	Science (biology, chemistry, physics). Electronics. Control systems. Economics. Systems dynamics. System thinking.	Manufacturing. Industry. Economic processes. Network systems (computer, telephone, telecommunication, traffic)

In technical applications simulation methods are used, when multiple parameters' influence on a process model is scrutinised, amongst which are parameters determined prognostically or by approximation methods. Simulation is most commonly used in engineering designing, modelling and static, dynamic and thermal phenomena analysis, in process analysis and its results visualisation. Simulation is also used in verification of NC programs, tool collision analysis, operating of storage, transportation and production devices [23].

2.4. Discrete simulation - operating

A model's behaviour consists of behaviours of single objects. In discrete simulation a process is presented as continuous chain of events. First the very first event is appearing, then the next one and so on. Each element's behaviour is a sequence of events. An event is a point in time, when an element changes its state. Elements in a system can be in one of the following five states:

- state of activity – in this state an element moves within a system,
- state of readiness – the state of elements, which are ready to progress to the state of activity,
- state of delay – the state, in which elements are waiting for known-in-simulation time, when they can proceed to the readiness state,
- conditional state – the state of elements waiting for the fulfilment of a certain condition,
- state of standby – it is sometimes recommended for elements to advance into a state, from which they could be easily restored thanks to the change of conditions in the model. This state is dependent on other elements, which are transforming elements from the state of standby into the state of readiness [15].

In the discrete simulation two types of events appear: planned and conditional. Both of them are causing delays in occurring of events in a simulation. The time of a planned event's occurrence is determined beforehand of the simulation.

Cycles of planned and conditional events, updating of statistical variables and creation of new events constitutes the essence of a discrete simulation – figure 17. In simulation programs events are taking place only in a foreseen time of simulation what means, that the process of simulation lasts up till the moment of the condition occurrence, which cannot be satisfied or until the end of time provided for the simulation. When all the planned and conditional events are completed within the time of running the simulation, the passing to a next planned event will take place. In the moment of an event's termination the simulation ends and reports are generated.

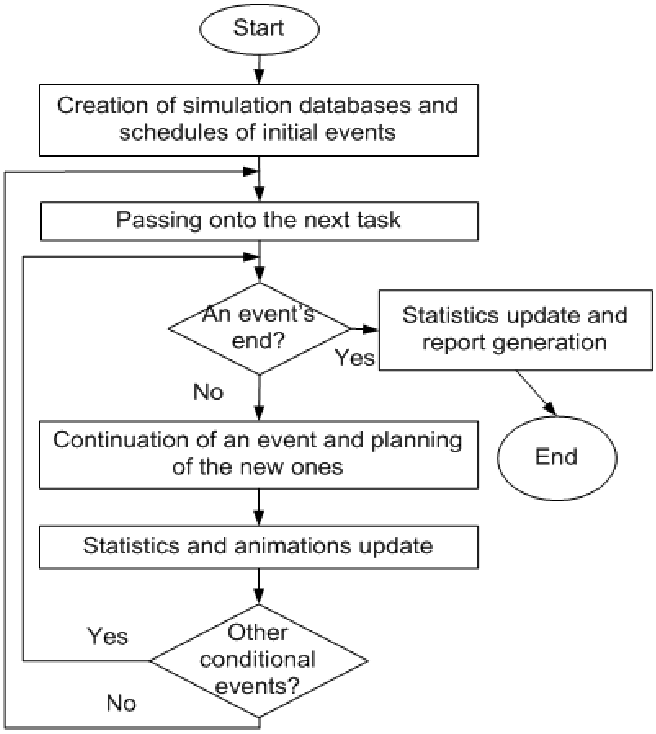


Fig. 17. Logic diagram of a discrete simulation functioning [40]

Discrete events simulation regards system modelling, where state changes can be expressed by means of discrete events [20].

There are three alternative ways of building models of discrete events:

- Event planning method,
- Browsing and choosing actions method,
- Process interaction method.

The comparison base for those models is the way of organising simulation calculations and reproducing in models three fundamental model elements: an event, a process and an action (figure 18).

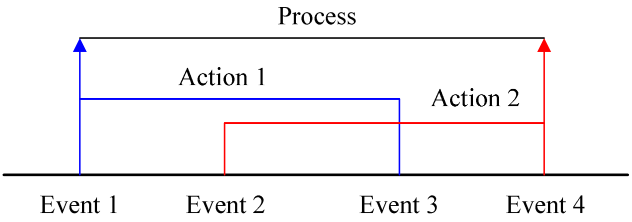


Fig. 18. Event, process and action [20]

1. **Event** – it is a change in the system state; it can be either a variable of attributes distinguished in the system, or an entering (deletion) of new objects (entrees), it has got a point characteristic. There are two event types:
    - unconditional events – directly dependent on time,
    - conditional events – indirectly dependent on time and determined by system states.
2. **Action** – a set of indivisible, at a given level of model conceptualisation, operations as the result of which system states are succumbed to a change.
3. **Process** – an ordered in time set of events connected to every single system prompt from the moment of its occurrence in the system to the moment of its disappearance from the system.

It's worth mentioning, that a process consists of actions, whereas an action is described by an event.

Discrete simulation model is characterised by the following elements:

- **system clock** – a dynamic object, recording the time of the real system (it also appears in continuous simulations),
- **system calendar** – a dynamic object containing a system clock and a set of information about an event (event type, event parameters),
- **system resources** – system statistical objects (single-channel, multi-channel service stations)
- **queues** – constitute separated elements not necessarily connected to the service station. Queues and service stations are closely associated with service centres [10].

2.4.1. Events planning method

Event planning method involves using in the model an object, which defines the succession of event types (e.g. an event calendar or a system clock) and a detailed description of activities, which are performed in the system, after a certain event takes place.

The implementation of events in a system takes form of time planning and types of unconditional events (events directly dependent on time), which are going to take place in the system. In a system, conditional events may also appear. In a discrete simulation, according to the event planning method, an emergence in the system of an unconditional event entails exercising a sequence of actions (related to that event) but also the ones concerning the conditional event.

The algorithm of the course of model simulation built based on that method is depicted in figure 19 and is as follows: after determining the initial conditions for the system, one needs to assume for the system time the time T_1 of the emergence of the first event in the system.

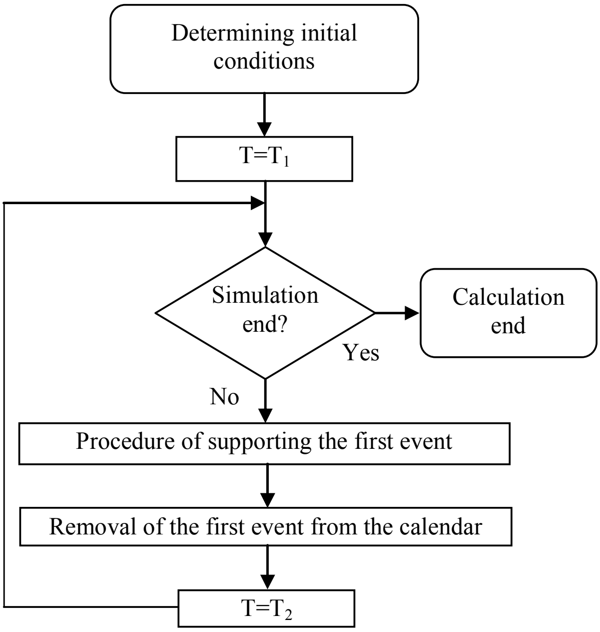


Fig. 19. Algorithm of discrete simulation course in event planning method [67]

After executing actions related to servicing of that event, one needs to remove the considered unconditional event from the calendar and move the system time to the T_2 time of the next event surfacing. All mentioned activities are ought to be repeated [67].

2.4.2. The method of reviewing and choosing actions

The method of reviewing and choosing actions consists of considering all actions in the system. The aim of digesting is to determine, which of actions should be initiated and which ended in the moment of event occurring.

Events' implementation into the system takes place by cyclical conditions checking, which should be fulfilled when events are occurring.

The algorithm of the course of model simulation, which was built based on that method is presented as follows (figure 20).

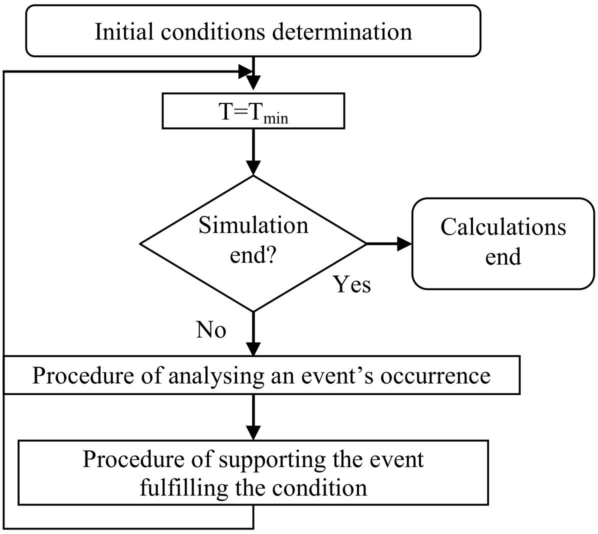


Fig. 20. Algorithm of discrete simulation course in method of reviewing and choosing actions [67]

After determining the system initial conditions, one has to conduct an analysis of the list of conditions of appearance of events for a given moment in the system time, in which the next event will take place (T_{min}). If for a particular event its appearance conditions are fulfilled it means, that the event has been chosen and the system time needs to be moved to the moment of that events appearance, and the procedure of actions related to that event run. All mentioned activities are ought to be repeated [67].

2.4.3. Processes interaction method

The method of process interaction combines features characteristic for both aforementioned and described methods, and it consists in grouping actions into processes performed upon single, dynamic objects (transactions) in the system and registration of their states from the moment they entered the system up till their disappearance.

Activities realisation of particular processes running in parallels in a system is carried out by cyclical checking of the events list and accordingly to the situation either activating or suspending the performance of a process. The number of processes in a system is equal to the number of appearing prompts. It means, that every prompt in a system is identified with a separate process. The course of processes is corresponding to the structure of the support service system.

The algorithm of the course of model simulation, which was built based on that method is presented as follows (figure 21).

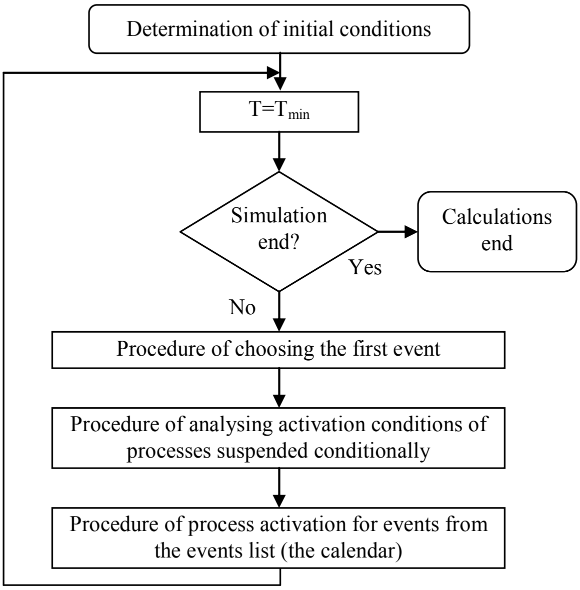


Fig. 21. Algorithm of discrete simulation course in processes interaction method [67]

After determining the initial conditions of a system, an examination of the list of event appearances conditions is required for a specific point in the system time, where the nearest unconditional event will emerge (T_{min}). All system processes, which are active in that moment, are realised in parallel to the T_{min} moment, that is to the point of synchronisation (coordination) of the system processes. In that moment an adequate event consideration as well as determination of processes activation order takes place. As a result of realisation of actions allocated currently to the examined event, some system process will be activated (serviced), whereas the other suspended (service awaiting).

The process activation can be served by the WAIT instruction (the delay time), which denotes the physical activity of the process, and in terms of the simulation the shift of the current system time by the designated delay time (e.g. service time). The process suspension can be described by the WAITTILL procedure (condition), which means the suspension (withholding) of the process performance until the moment, when the given condition is fulfilled, e.g. the service station is non-occupied [67].

Comparison of simulation methods of discrete processes is presented in Table 3 and Table 4.

Table 3. Comparison of simulation methods of discrete processes (Characteristics)

	Events planning method	**Method of reviewing and choosing actions**	**Process interaction method**
Characteristics	• there is a detailed list of planned events, • times of prompts' appearances are taken into account, • prompt selection is made by simulation controlling program, • starting and ending actions is an event, • every diagram includes one event, • key term: events planning.	• lack planned events, • every object has a clock, • lack of logic tests typical for events planning method, • model description by describing events, • method is not popular.	• concepts conjunction of events planning method and method of reviewing and choosing actions, • description by means of processes (process – separate prompt), • possible to ignore lapse of time (snapshot observations), • precision required in formalisation, • every diagram includes several events, • key term: waiting, delay

Table 4. Comparison of simulation methods of discrete processes (Application, Method characteristic, Method algorithm)

	Events planning method	**Method of reviewing and choosing actions**	**Process interaction method**
Application	• High number of prompts • low number of actions	• High number of actions	
Method characteristic	Utilisation of structure called prompts set about events or calendar	In every simulation cycle conditions under which every event have taken place are checked which are time and system status dependent. It means the possibility of independent description of conditional events (conditioning the problem of order of checking logic conditions)	Procedure conjunction of cyclic events planning by reviewing system states. Dependent on time and conditional events are grouped into processes associated with system objects. Events constitute process synchronisation points.
Method algorithm	1. Determination of initial values. 2. Checking condition of simulation end (if fulfilled, calculations should terminate). 3. Adoption for system time the value of time attribute of first message from calendar. 4. Procedure execution of the first event in the set. 5. Deletion of the first message from the prompt set about events and progression to the second step.	1. Determination of initial values. 2. Checking condition of simulation end (if fulfilled, calculations should terminate). 3. Flag scanning "Status change in the system" 4. Checking for every event the condition of its occurrence (if fulfilled an appropriate service procedure should be completed and flag set to "status change in the system" 5. If the flag is set to "status change in the system", advance to the third step. 6. Simulation time shift and advancement to the second step.	1. If the station is free advance to the fifth step. 2. Insert a task into the queue. 3. Execute the operation WAITTILL (free station). 4. Remove the task from queue. 5. Occupy the station. 6. Execute the WAIT operation (service time). 7. Release the station.

The scheme of running an exemplary simulation is shown in the figure 22.

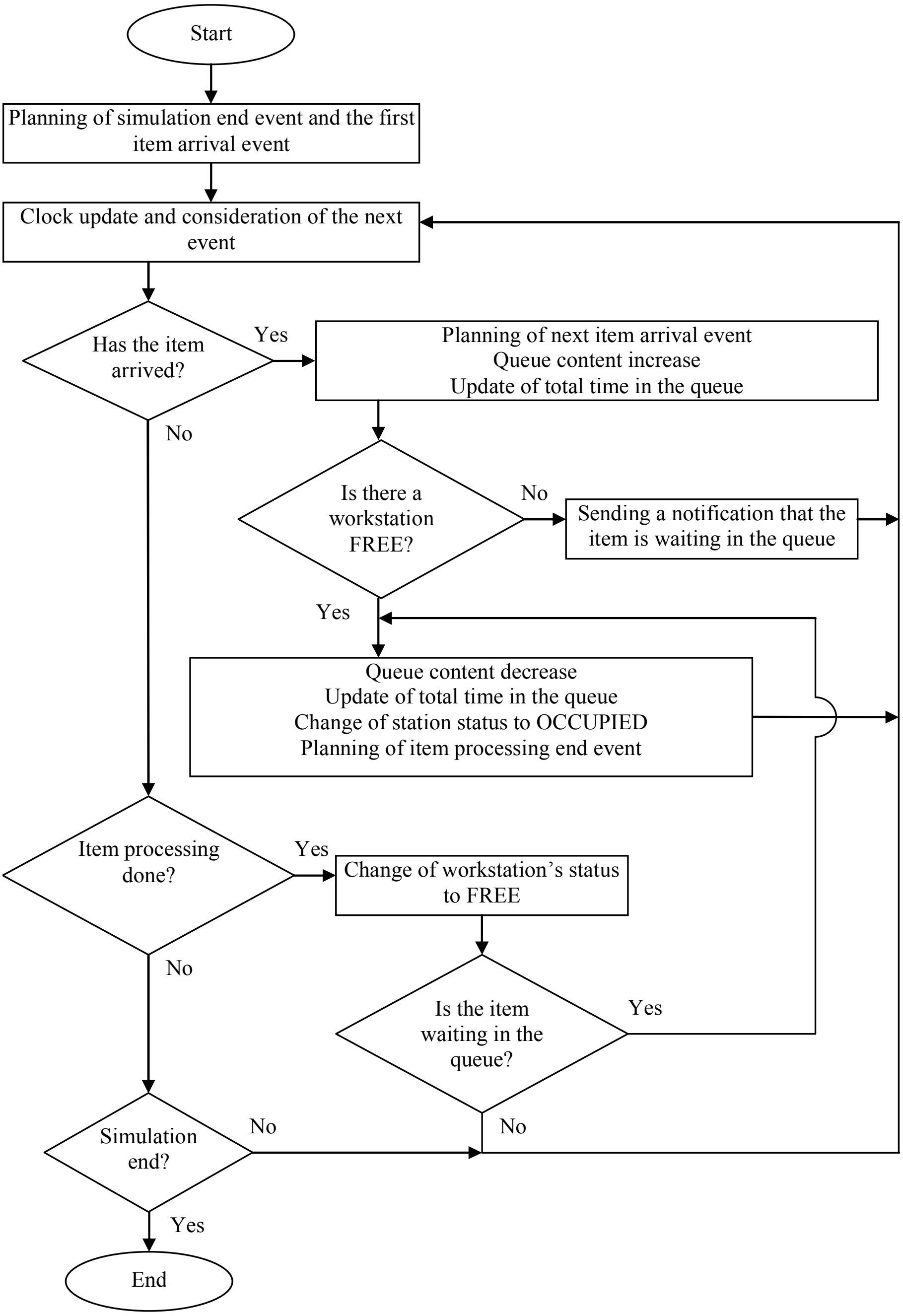


Fig. 22. Diagram of an exemplary simulation course [40]

2.5. Simulation model of a production system for series production

During literature research it came to the daylight, that there were a limited number of described simulation models of production systems, methodology of leading such simulation projects especially in case of applications in industrial processes realisation. For modelling production systems, in order to elaborate a layout, determine quantity and structure of transportation means, material flow optimisation, a model should include objects representing workstations of machines and devices, personnel, transportation means, tasks to perform and working space.

2.5.1. Structural elements

Proposed standard model includes the following components:

- items – objects that make up the goods manufactured in production processes,
- machines and devices – stations where objects are processed, assembled, stored and so one,
- resources – personnel, transportation means used in the manufacturing process,
- routes – objects or resources transportation paths within a system.

In figure 23 a set of data was collected characterising proposed production system model for series production.

Items are objects situated in the model, representing parts and products manufactured in the real production system. Those objects within the system hold the following features: volume, size and assigned attributes. Items are travelling along one or more routes within the system and are transported to machines and devices to complete predetermined technological operations, repacking, storing and order picking activities and so on. They could be manufactured inside the system or supplied from the outside – e.g. as parts made in cooperation. Mostly objects are leaving the system after having passed through certain amount of machines and devices. An item's size is essential to take into account when modelling e.g. a conveyor. As defined items are also qualified elements such like chips, greases, tools and auxiliary tools.

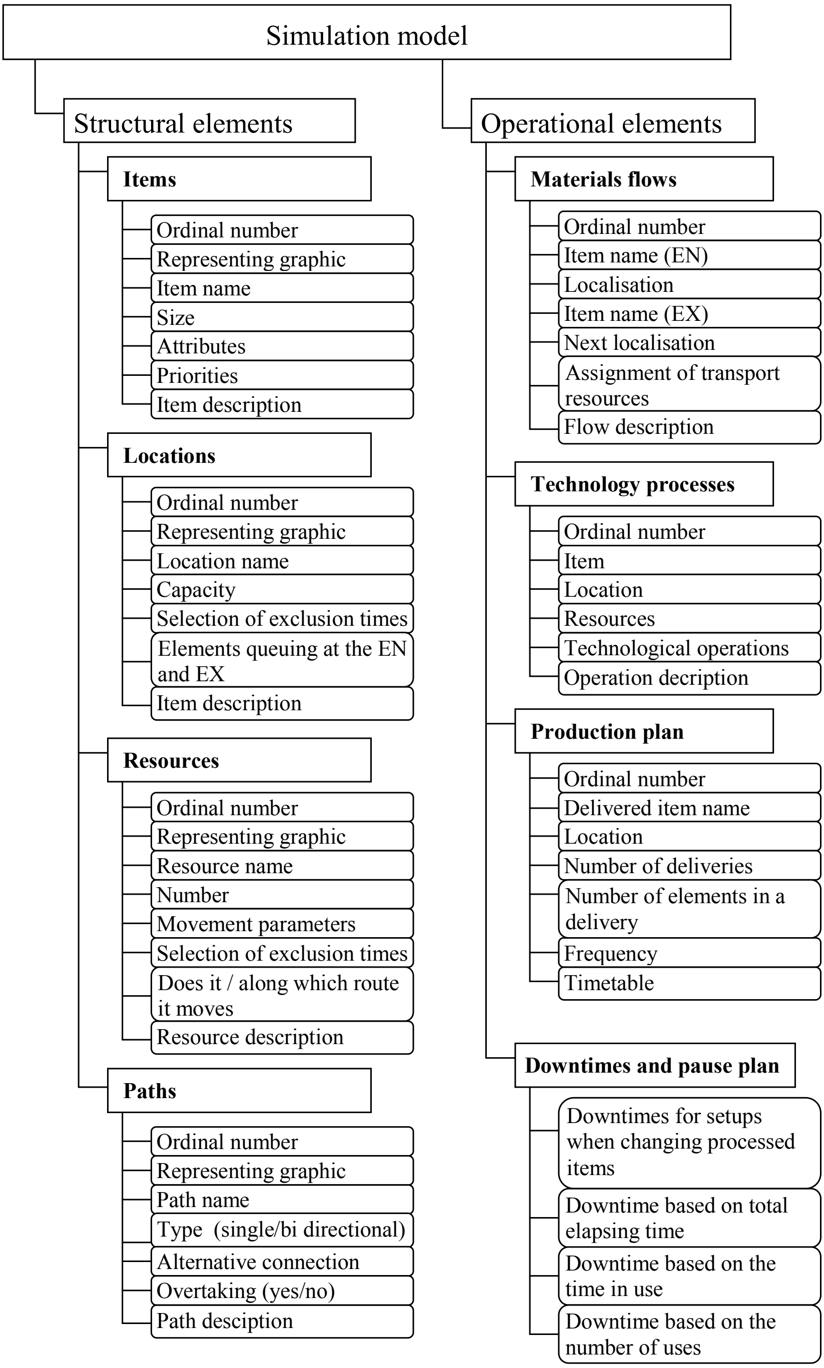


Fig. 23. Arrangement of data about structural and operational elements constituting a simulation model for series production

Machines and devices mean places, through which items are passing to be processed, machined, await or make decision about referring to a particular place. It can be a workplace, machine tool, checkpoint, queue and a storing area. Machines and devices gave got a determined capacity (volume) and can have a determined availability time. They can also have special entries and exits based on rules of FIFO, LIFO, at the highest priority and others. After running the simulation, we usually acquire an average number of items for given machines and devices, as e.g. an average number of customers in a queue, or an average quantity of parts in a container. Time data is also significant, revealing how long an item spends at a workplace, yielding statistics informing about utilisation times, downtimes or pauses in operation of machines and devices.

Resources are factors used for performing a certain process, operation, procedure and so on in a system. They can be static or dynamic depending on whether they are mobile within the system or remain stationary. Usually they comprise employees, means of transport, tools and instruments, greases, chips etc.

Resources can be animated (people) or inanimate (tools). The most important difference between items and resources is, that items after entering a system are moved around it according to a predetermined process, after completing which usually are leaving it. Resources though, do not have an appointed sequence of flow and remain in the system.

When conducting a simulation of production systems, our subject of interest is the way resources are used, what specific quantity of resources is needed and to what extent an object processing is dependent on a resource's availability, the time it takes for a resource to answer to demand signals. Transportation resources are employed for moving objects about within a production system. They can be gantry cranes, manual transport trolleys, forklifts or conveyor belts. They are dynamic resources, normally capable of transporting a diverse range of objects. In production systems there is often a lot of loading, load transfer or unloading points.

Routes determine paths for items and resources. They can be single or combined into networks. Itinerary routes need to be precisely determined between two points, because it ascertains the distance between workplaces. Routes combined together and formed into networks are normally encountered in manufacturing processes. In production enterprise models routes are joined together in order to create transportation paths for gantry (overhead) cranes, for diverse range of transportation trolleys, conveyors etc.

2.5.2. Operative elements

Operative elements decide, how various system elements are acting and how they are influencing each other. To operative elements we include:

- material flows,
- technological processes,
- production plans,
- downtime and repair plan.

Material flows are predefined sequences of transportation activities performed upon items, to move them from one workplace to another. Material flows determine where an item should head afterwards of completing action at a particular machine or device and specifies choosing criteria, when an object has got multiple destination workplaces.

Sometime an item can be directed to an excess of one machine or device. In that case the necessity of choice arise, hence a rule or a criterion must be in place, stating which workplace should be chosen.

Technological processes define what will happen to a given item upon its arrival at certain workplace. In case of modelling there is no need to precisely follow the predetermined activities intended for a particular operation e.g. during machining. Whereas it is essential to take into account the time, which is required to perform an operation, which resources are utilised and accumulate data on an operation's or procedure's characteristic features, which could have an influence on the production system's operation.

In case of complicated operations having a substantial effect on a production system, it may occur to be necessary to define conditional clauses, assigning to them concrete variables or other conditions.

Simulative *production plan* determines the time, number, frequency and place for items entering production system model. The timeframe of a production plan is dependent on the target appointed to a system model, and items can appear in the system model individually or in groups.

Downtime and repair plan – resources as well as workplaces have often planned and unplanned periods of time, when they are unavailable. The following downtimes are included:

- tooling time when changing processed items,
- pauses based on passing time,
- pauses based on time in use,
- pauses based on utilisation number.

Unfortunately, data regarding downtimes are seldom available in a form favouring “processing”. Chiefly they are garnered as aggregate data, and rarely as detailed data. Depending on the character of collected data and the extent to which a simulative solution is required, downtimes can be treated in the following manner:

- downtimes ignoring,
- ordinary processing time increase,
- using the average value of time expected to failure (MTTF – Mean Time To Failure) and expected average time of operating time between failures (MTBF – Mean Operating Time Between Failure),
- using statistical distributions for inter-repair times and repair times,
- both operating and idle time of a machine,
- solely a machine’s operating time.

Downtimes based on passing time should be defined as a function of clock time. Whereas a downtime, which is related to an action, should be defined as a function of time in use. Wrong downtimes determination on the basis of a complete passing time, in a situation where it should have been determined based on the time in use, it artificially overvalues the time interval between failures by counting in the downtimes. It also suggests, that during intensive devise utilisation exactly the same number of downtimes occurs, like during times of low intensity equipment utilisation. Equipment failures should be based on the time in use, and not on the complete passing time, because it contains the time of action, idleness and downtime.

2.6. Advantages and disadvantages of using modelling and simulation

For the majority of companies, the benefits of using simulations will have been visible in a distant time horizon. The following advantages can be spelled out:

- right decision making – simulation allows testing of every aspect of proposed changes, because change implementation into the real system entails monumental costs,
- compressing and expanding the time scale – slowing down and accelerating of the course of simulation allows to track very accurately events occurring in an analysed system,
- understanding „why" – we often want to know, why certain phenomena are taking place in the real system. A simulation allows for answering that query by the reconstruction of that phenomenon and running an analysis. It cannot be achieved in the real system, because one can't neither control nor observe holistically the entire system,
- capabilities discovery – the biggest benefit of using simulations is, that on the built model one can examine and test new solutions without the need of pricey experiment conducting upon a real system,
- problem recognition – a modern factory or an organisation is a very complex entity, what causes an impossibility of probing all interactions in a given moment,
- restrictions recognition – a simulation used for the recognition of bottlenecks will allow to discover consequences of delays in the production process, flow of information, materials etc.,
- system understanding – a simulation allows to understand a system and appropriately design it.
- factory plan visualisation – allows inspecting a system from different angles and from different distances.
- agreement building – a system analysis by a simulation gives an objective underpinning for the decision making process.
- preparation for changes – provides answers to the questions of „what, whether". A simulation experiment facilitates an examination of different alternative decisions [50],

- repeatability – it is a rare occasion that an experiment can be repeated in a real system under the same conditions – whereas simulation provides strict repeatability,
- security – one of the tasks of a simulation could be the assessment of a system's performance under extreme conditions. Due to safety, it is often the only possibility to run an analysis of that kind [31],
- economy – a simulation's cost is far less than the expenses on experiments done in the real system,
- staff training – employees are making decisions, which are input variables to the model. In that manner they learn on their mistakes. That solution is less destructive and cheaper;
- methodical and iterative definition of the requirements for the designed system.

Simulation disadvantages:

- good simulation models are expensive and their preparation consumes a lot of time,
- every simulation model has got a unique character. Its solutions cannot be utilised for analyses of different decision problems;
- allows for preparation of alternative decisional solutions in the following experiments, but those are not optimum solutions for every conditions.
- simulation models generate answers to questions relating to concrete and variable conditions. A decision maker preparing a decision has to take into account all determinants and restrictions of analysed decisional variation.

Simulation and empirical experience

The superiority of simulation over empirical experience manifests itself in the fact that:

- experimenting with a real system is very expensive and sometimes completely impossible,
- computer simulation is always repeatable and non-destructive,
- a model's reaction obtained during a simulation is easy to interpret and apply further (e.g. in order to optimise a model),

Apart from that a simulation gives:

- possibility of probing both real and hypothetical systems,
- possibility of eliminating the influence of the factor of system observation time,
- repeatability of simulation experiment under the same conditions,

- possibility of research under conditions being either difficult to obtain or impossible to obtain in reality at all,
- possibility of conducting hypothetical research with the need of building a prototype,
- simulation is characterised by field universalism, facilitating construction of simulation models of any dynamic systems.

Simulation drawbacks:

Amongst simulation drawbacks we can list:

- lack of universal methods deciding about a model's built correctness,
- lack of systemised rules of creating simulation models for a particular area,
- lack of possibility of automating model building procedures,
- comparatively high sensitivity of simulation research effects to "malpractice" during building and utilising simulation models,
- relative time-intensiveness and high construction costs of a model for needs of practice.

The fact needs to be accepted, that a created model would never precisely describe a complicated real system. Therefore model creation is a real art and requires loads of experience, proving very helpful when choosing appropriate variables. A large number of variables would be omitted, without a shadow of a doubt, otherwise wrongly included.

Simulation mistakes:

The most difficult yet the most important step in the process of simulation is determining the objective system. On this stage's precision is reliant the adequateness and usefulness of the whole simulation's outcome. Other simulation mistakes result from:

- incorrectly determined research goal,
- inappropriate level of detail of the model,
- lack of sufficient proofs of model credibility,
- use of incorrect methods and techniques of model construction,
- inductive resulting, transgressing beyond an experiment's environment,
- omission of the user in the model building process,
- negligence of communication sphere with the user.

By following the latest development directions of simulation and its applications, it's easy to reach the conclusion that it increasingly approaches notions related to AI (*Artificial Intelligence*), and particularly its branch specialising in building expert systems - ES (counselling). There is even an opinion that in the future those systems are going to be called expert simulation systems. Despite the success of expert systems in various fields of knowledge, their application in organising and managing still stumbles across certain difficulties. Simulation can help to overcome at least some of those difficulties [31].

3. Application of simulation modelling in Organisational Production Preparation

3.1. Application of modelling and simulation in designing production systems

Technological progress allowed for production of quickly changing goods, and also has caused general changes in views about production systems' organisation. Production system in its dynamic aspect has become subject of interest along with an increase in demand for modelling and simulation methods of such systems' operation. In order to develop methods of modelling and simulating, influential factors analysis needs to be conducted in terms of their impact on a system's organisational solutions, that is, they had to be classified and quantified, their mutual dependencies needed to be explored as well as their traits generalised. A production system can be decomposed into series of cooperating with each other subsystems – figure 24.

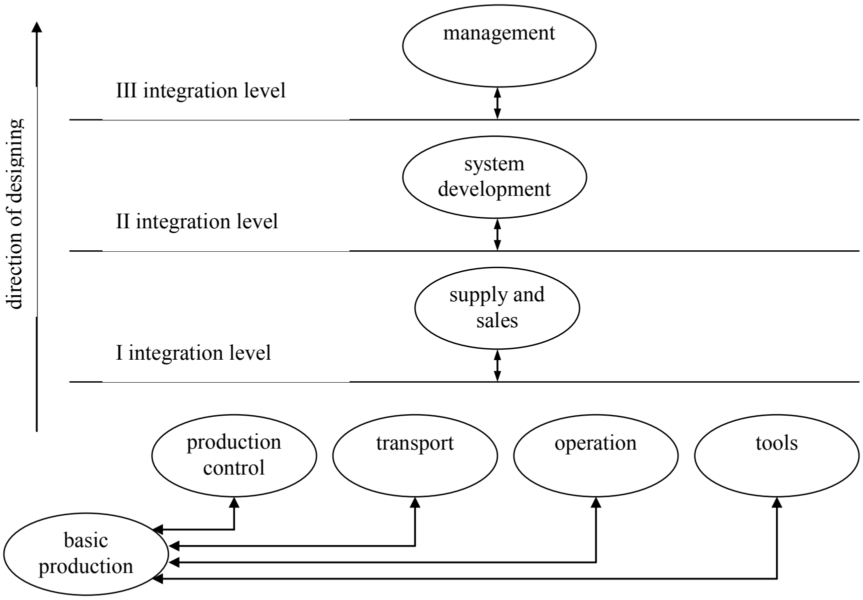


Fig. 24. Manufacturing system division into subsystems [44]

Such division has to take into account though, apart from taking place interfaces between subsystems, their mutual relationships, also the order of designing, which is strictly determined. Each of those subsystems has got different tasks, is linked with others and has got a predefined place in the process of building a production system [44].

Authoritative outcomes of simulation research can be obtained only when an integrated enterprise model is built, which comprises all components of a production process, being: cubature infrastructure, means of production, material resources, human resources, products, processes structure and their topology [25]. In order to facilitate analysis of production orders' realisation, an enterprise model has to be built beforehand, where should be included integrated main processes and assigned to them data.

To the most important components of an integrated enterprise model, used for simulation we can include:

- planning models of an enterprise describing its organisational structure (centralised, scattered, multi trade, specialised etc.),
- structure of competences flow and decisions in the area of marketing, production preparation, production execution and logistics (along with storehouses) and service,
- flow structure and documents' type in individual development phases and product life cycle,
- rules of planning and production control,
- structure and traits of diagnostic systems supervising machines and production devices,
- rules and tools of monitoring the course of design, logistic, production and service orders,
- geometrical models, technological and other generated by a CAx system, which can set the base for generating data for simulation models,
- simulators and editors of models and data used for repeatable modification analyses (current processes modification or their courses resulting from temporary needs or breakdowns),
- data banks, which are source of indispensable data and base for conducting simulative analyses.

In the current economic climate enterprises need to strive in, those should be acknowledged as the most important constituents of enterprise management, which describe the real conditions under which processes are performed [21].

3.2. Levels of simulation's applications

Considering a user's needs (production engineer) with respect to simulative analyses and tools for their conducting in a production enterprise the following fundamental areas can be indicated:

- product development and projects management – currently simulative analyses and tools are the most essential methodology when implementing new product into production,
- simulation and visualisation of a production order's course,
- materials flow, transport routes planning and layout plans.

Contemporary simulation methods and tools are employed usually in large enterprises (research shows, that up to 83% of planning and engineering analyses) in comparison with small enterprises – 48% utilisation [42]. It comes as no surprise, that the most frequent use of simulation was observed in the automotive industry, and that is both by final producers as well as components suppliers – figure 25. It is a dynamic and particularly important part of industry. Its products are burdened with very high quality requirements, low production costs are requisite and constantly new models of goods has to be devised. Those conditions constitute the strategy of every car maker.

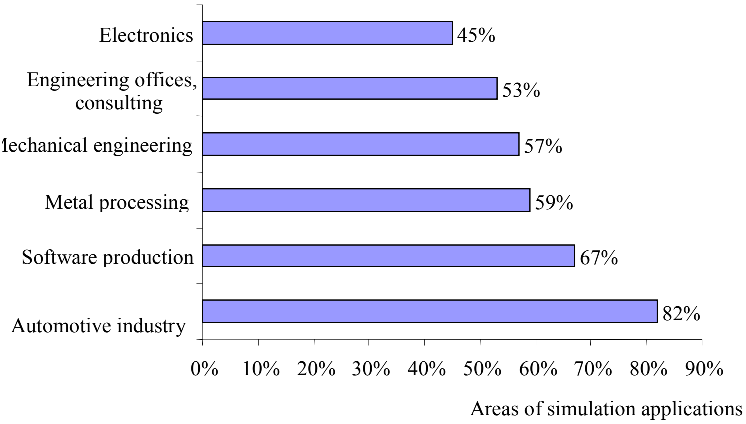


Fig. 25. The most common cases of using simulation [42]

Subsequently simulation occupies a highly vital position in the field of software production, metal processing industry and mechanical engineering, advisory and consulting and in electronic devices engineering. Particular development of those techniques and tools came with the popularisation of engineering techniques based on graphical editors available at a designer's workplace. Earlier used simulative methods were allowing only for editing the simulative analyses results by means of characters, what substantially restricted their application mainly to researchers creating methods, models and interpreting analyses' outcomes. Techniques of graphical processing, especially 3D models, play a key role in further development of simulation methods and tools. The results of research conducted in German automotive industry, shown in figure 26, can serve as an example.

Along with the development of computer techniques and graphical systems, especially those based on 3D models, the interest in those simulative techniques has risen.

3D models utilisation is highest in:

- Technical product development – 49% of applications (especially geometric modelling and analysis by finite element method),
- technological elaboration of production processes – 23% of applications,
- material flow planning, production processes realisation and planning of machines and devices arrangement – also 23% of applications,

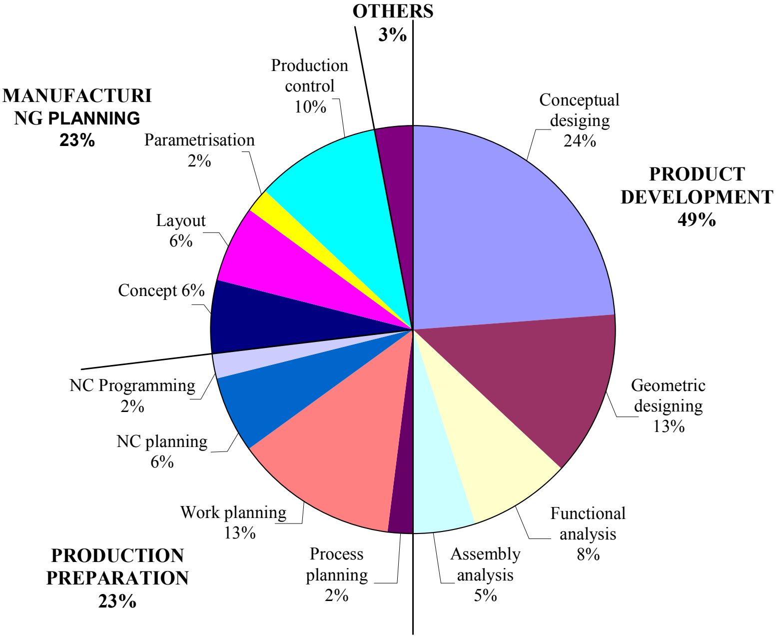


Fig. 26. Application of 3D models in simulation [33]

In important argument advocating utilisation of the latest simulation methods and tools at the every stage of product development and production process planning is a so called “rule of ten”, developed at Sony Corporation. It indicates, that costs of correcting mistakes done during a new product development phase along with their production processes, before their market launch should be multiplied by ten for the developmental phase. It means, that if the cost of mistake elimination in the conceptual phase equals 1, then in the technological planning phase it equals 10, in the prototype building phase 100, during the zero batch 1000, and costs of the mistake removal in the launched product equal 10000.

Primary goals of employing simulation methods are presented in figure 27. As the most important, users of simulation systems identified:

- functional optimisation,
- functional research,
- research and lowering of risk.

An essential issue in simulation modelling and analysis of production processes is appropriately recognised data. There are often differences in data determined, based on forecasts and long-term production programs in relation to real data. Hence outcomes of simulative analyses conducted as a part of planning works are often discrepant with results obtained from surveillance of real manufacturing processes.

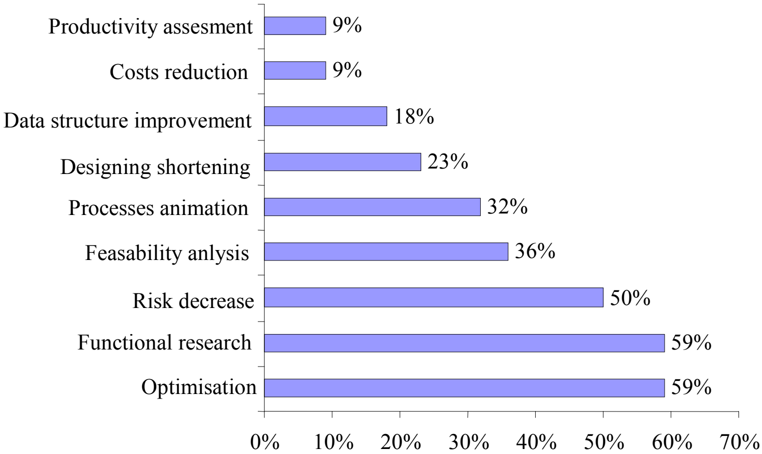


Fig. 27. Main objectives of applying simulation models [33]

Simulation is used for more effective selection of materials for goods as well as designing new products. Application of simulation in the area of enterprise planning and manufacturing comprises the level of devices, cells and components. All three levels are distinguishable by the scope of planning, simulation model along with simulation tools (table 5).

Table 5. Levels of simulation application [22]

Level of planning	Scope of planning	Simulation model
Device	Layout analysis Materials flow/Logistics System efficiency Manufacturing rules Control strategy Disruption control	Flow simulation (rough)
Cells	RC-NC – programs Order flow Socket's layout Path time analysis Collision analysis	Flow simulation (accurate) 3D – movements simulation
Components	Factory's resources utilisation Process parameters Tools Auxiliaries	MES 3D – movements simulation

At the device level is listed Layout planning, system productivity determination, but also disturbance and system control analysis. At the cells level significant meaning has also got layout planning, where emphasis is put on stations' arrangement in individual cells.

Examples of issues, where simulation methods and modelling may find their use are shown in table 6.

Simulation is employed at different stages of product development process, from its concept formulation, structure planning and material flow up to the launch and its maintenance (figure 28).

Table 6. Examples of process models in a production enterprise [34]

Model	Application example	Time horizon	Model type	Required data
Strategic development e.g. at the level of enterprises' holding	Market study, order forecasting and planning, financial result forecasting, the concept of a production system project	Strategic (long-term)	Static and dynamic models, usually continuous, but in some cases discrete, scholastic	Data aggregation at the enterprise holding rank
Production management at an enterprise's level	Order and resources planning, initial production planning, Classification at an angle of production management, Project and production equipment specification concepts	Tactical (middle-term)	Usually dynamic models or discrete deterministic, moderate level of aggregation	Data aggregation at an enterprise level
Production management at the level of production departments	Production orders planning, various production strategies study	Operational (short and middle-term)	Dynamic, discrete and deterministic on-line models, deterministic, scholastic, off-line models	Data from production departments

For every area of application, cycle phase and planning level, different simulation functions could be assigned. Although there are three fundamental areas, which a simulation should comprise:

- time,
- costs,

- resources condition.

In the area of TPP (Technical Production Preparation) the time simulation consists in determination of the probable time of formulating a construction, technological and assembly documentation as well as particular phases of their realisation. It demands aggregation, processing and archiving substantial amount of construction, technological and organising data. Simulation facilitates tracking of consecutive stages and design phases and checking the possibility of optimisation of the composition's course.

Cost simulation in the TPP area allows for determining costs of elaborating the technical documentation and subsequently seeking for cost-cutting solutions.

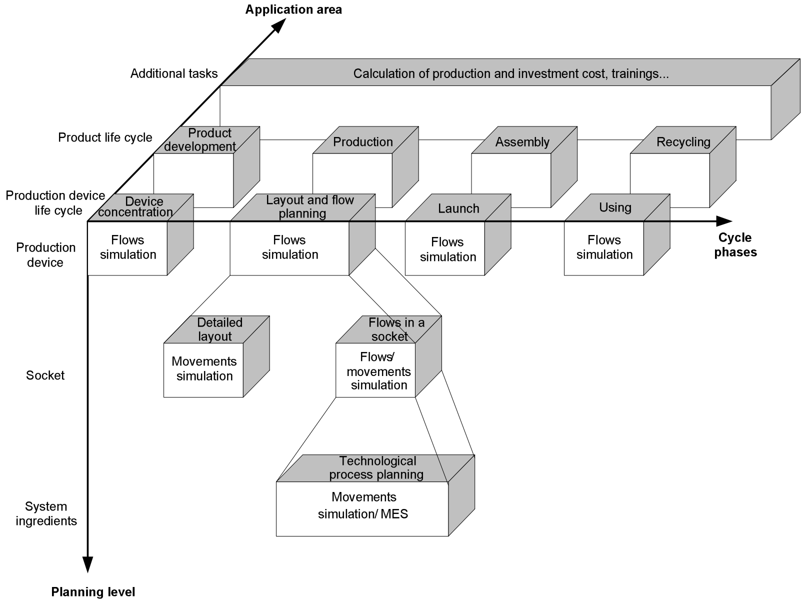


Fig. 28. Simulation application possibilities [72]

When developing new products or processes many solutions' variants are considered, which are taken into account before committing to an optimum solution (figure 29). Simulation methods are serving in that case as auxiliary tools for making decisions. Simulation can often find only partial solutions, which can substantiate finding the best variant. Simulation can be applied in order to accelerate product development processes and to evaluate the capabilities of successive variants. By application of simulation methods design cycle shortening can be achieved, along with errors reduction and improvement of a product and processes as well.

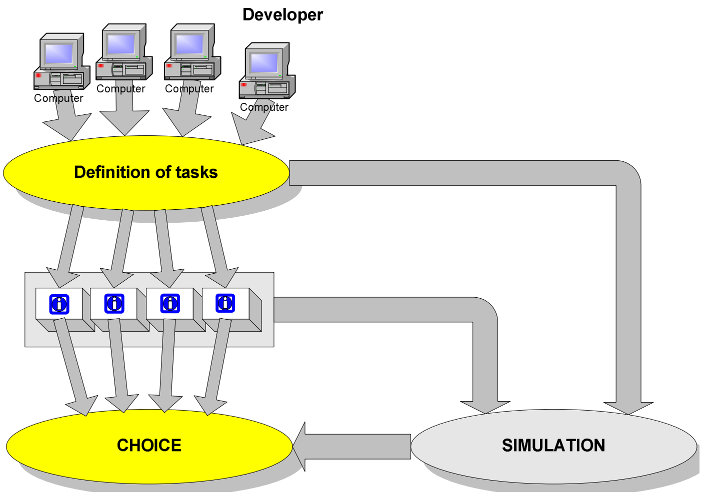


Fig. 29. Simulation as a method of decision supporting [21]

In case of modelling and simulating phases of product development, models of processes or enterprises are not presented nowadays as one-dimensional choice of optimum solutions, but as a conjunction of many partial solutions and their permutations.

A product consisting of numerous individual components, in accordance to which an entire production process can be determined, is combining various production technologies in an enterprise with adequate competences of specialised staff (figure 30).

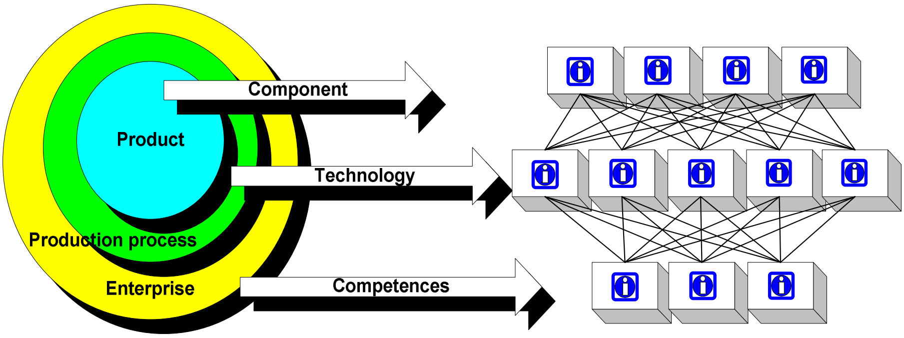


Fig. 30. Future applications of simulation methods [21]

Design issues, including modelling, simulation and evaluation of technological assembly processes, is mostly covered on a random basis and touches usually on design for constructability, determination of assembly order, assembly line balancing or a chosen machine parts module combining technology. Making attempts to use e.g. Petri net theory for modelling and simulating technological assembly processes usually refer to chosen issues [27].

Possibilities of integrating problems of computer aided products designing and technological processes and planning as well as production scheduling are provided by distributed databases systems. Those systems consist of certain number of spatially distributed computer systems, which are equipped with facilities for storing data and can be mutually communicating with each other by means of data transmission links. Rules of integrating data of aforementioned problems are depicted in figure 31, where relationships biding subsystems together are marked:

- managing and leading an enterprise,
- designing of products and technological processes,
- production planning and production scheduling [1].

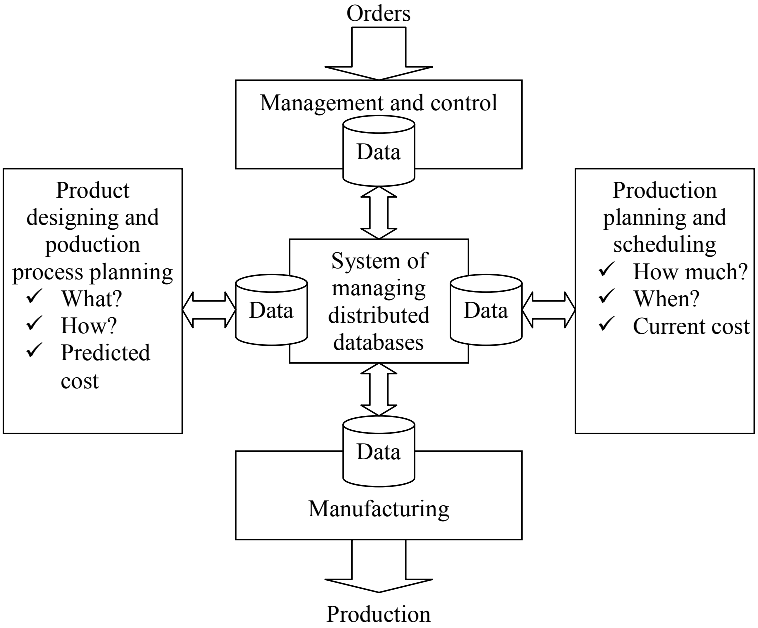


Fig. 31. Role of distributed database in controlling information stream flow [1]

Distributed databases systems constitute one of paths of further integration of simulation tools with the aforementioned subsystems.

3.3. Simulation in product development

Relatively the fewest simulation models had been formulated and created for the research and assessment of development phases of product development, because integrated data models are required to describe difficult to formalise conceptual phases, along with initial shaping of construction form of a product. In this product development phase frequently employed are methods and tools intended to monitor the course of design works and creating a functional structure and the organisational form of the design team (Hence they are typical tasks of tools applied in *Project Management*).

The most encountered models applied in simulation of integrated product development's phases, realised in the mode of Concurrent Engineering are depicted in figure 32.

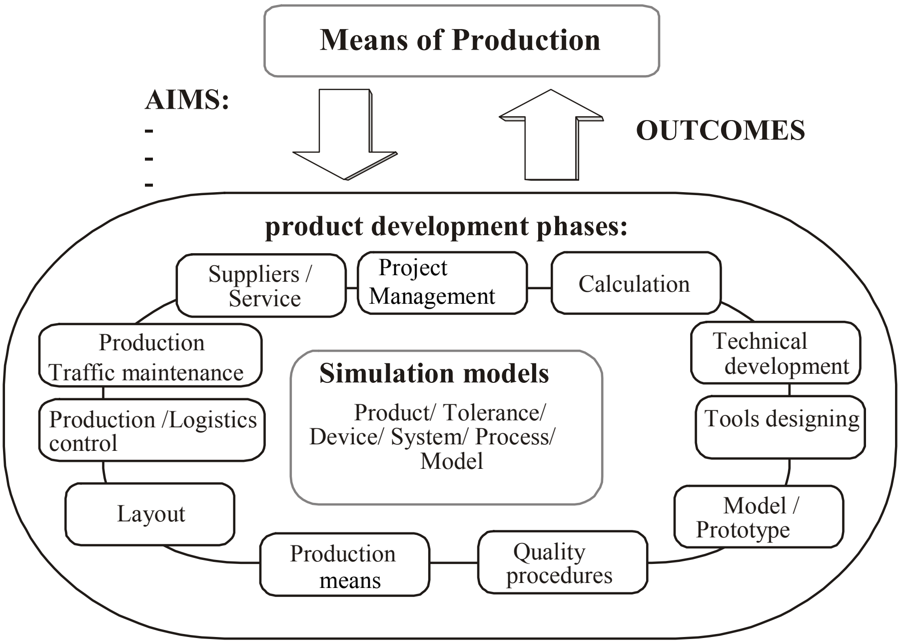


Fig. 32. Simulation models in integrated product development in the CE mode [35]

Whereas figure 33 presents benefits of using simulation techniques in integrated product development (normally used repeatedly in different projects) and in case of a one-off application.

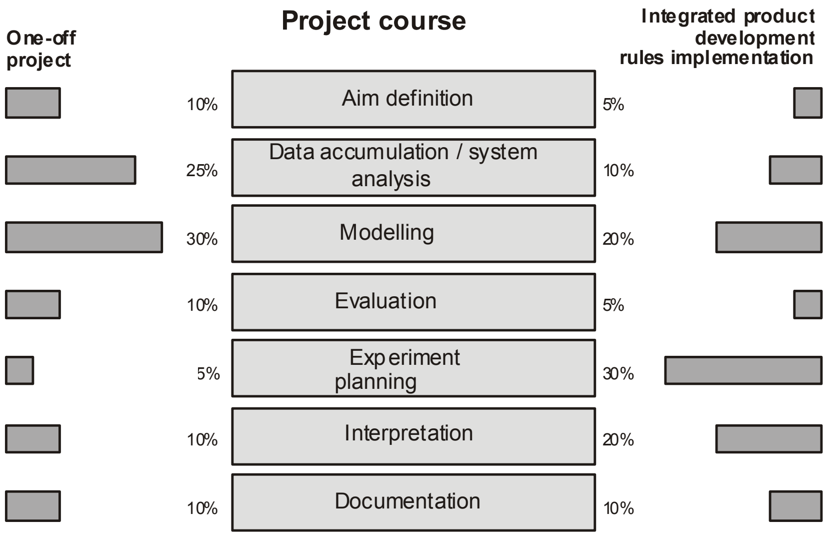


Fig. 33. Simulation application in integrated product development [35]

Not only should stress be put on the integration of simulation models facilitating very wide analysis of an individual product development phase, but also an emphasis needs to be put on the necessity of integrating and synchronising, organisational actions, characteristic for concurrent designing and group work. In that case plentiful other functions belonging to manufacturing phases can be distinguished which are saved within a simulation model, because during developmental product phases not only the own production capacity should be considered, but also the possibility of cooperative order outsourcing. Particularly important is implementation of simulative analysis methods and evaluation of integrated product developmental phases (designing). Here, above all one can exploit advantages of repeatable phases in conducting analysis in numerous projects being realised, as well as data resources from CAx systems can be used, which are generated in a heterogeneous design environment of engineering tools.

3.4. Simulation in material resources management

If using simulation methods in the initial phases of a product life cycle (designing and forming of the construction form) does not include material resources required in a production process, it is necessary when simulating production processes, because those resources are playing a major part in cost-intensity of a production.

Basic data needed in simulation are determined on the basis of the product model as well as the production process model (including production infrastructure and production plans generated in PPC systems) – figure 34. Owing to the processes and their models complexity, a user should have at his disposal interactively accessible model modification functionalities along with ones for simulation plans configuration and their results interpretation (specifically in case of graphic visualisation and interpretation of a simulation's outcomes).

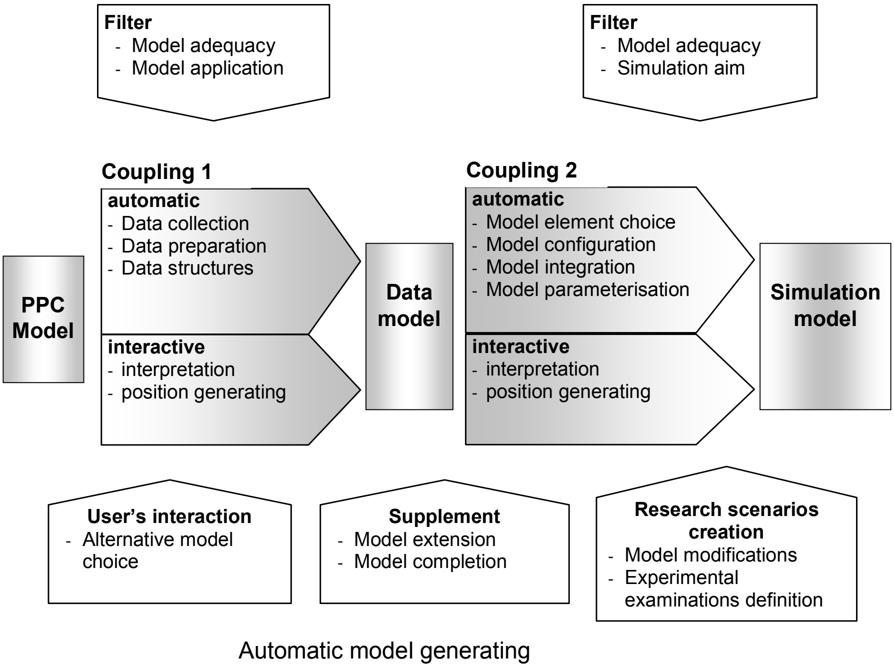


Fig. 34. Simulation models generating in a production process [48]

Characteristic tasks and functions are ascribed to management (control) of material resources. Such function is also created in purpose-made MRP, MRP II and ERP systems. However, they are usually stipulated mainly to resources planning and warehouse stocks management. They could also be data generators for simulation systems, whose primary functions are process and resources optimisation. A few areas can be named:

- preliminary material needs planning,
- transport routes and operational buffers optimisation,
- current production optimisation and control,

- ➢ transport logistics optimisation and others.

These analyses can refer to an entire enterprise, an isolated facility or a branch and even to a single cell – figure 35.

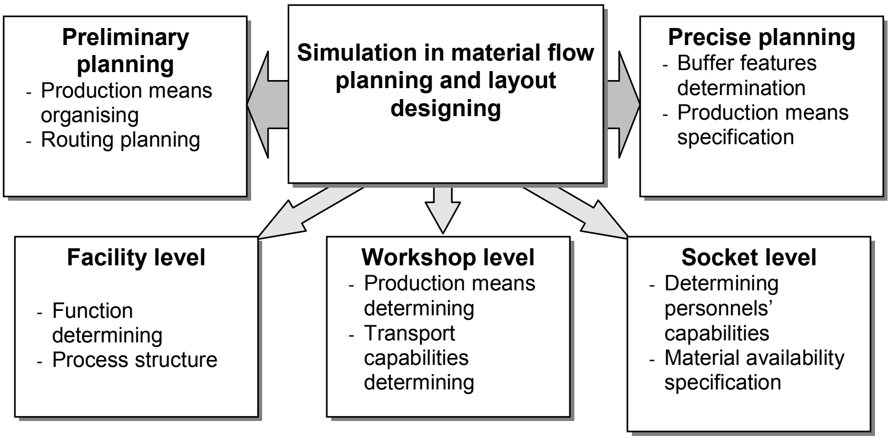


Fig. 35. Simulation in material flow planning and control [48]

Classified simulation models' aims in the optimisation of resources controlling and materials flow are presented in figure 36.

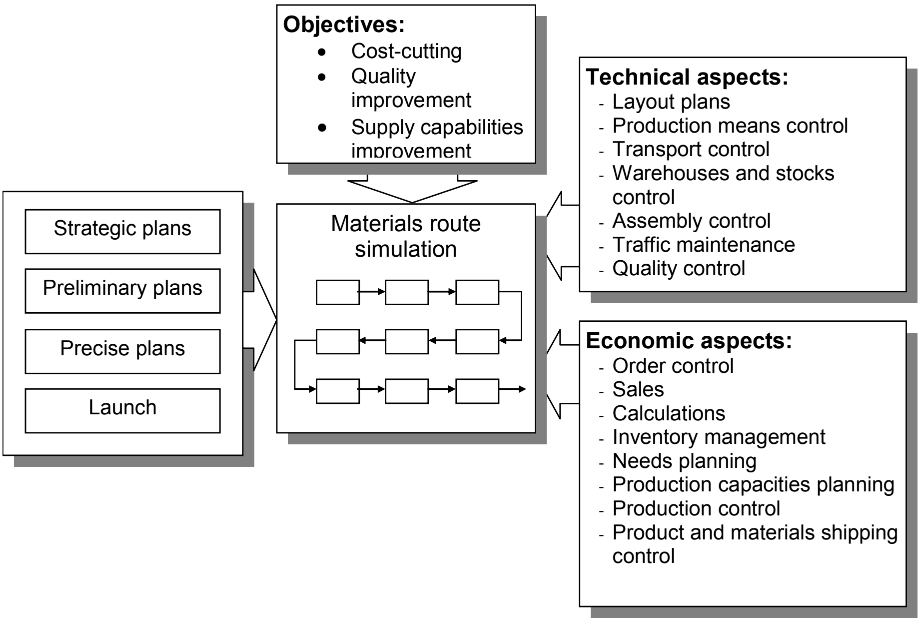


Fig. 36. Simulation models' functions in optimum controlling of materials flow [48]

As centre aims are appointed, held currently in highest regard determinants of a competitive production: low production costs, high product quality, flexibility and supplies timeliness. Two major aspects were indicated of material flow controlling, namely technical aspects and economic aspects.

In the first instance that refers in particular to planning and organising of production infrastructure and to the control of machines, warehouses (stocks) an in-facility transport. Economic aspects enumerate: order control (and their course optimisation), inventory management, cost calculation and production capacities control and optimisation.

Conducted analyses can have a strategic, preliminary and long-term character as well as precise and short-term. In order for those analyses results to be useful, one needs to build adequate simulation models and acquire appropriate data.

3.5. Simulation in spatial production infrastructure planning

The following problems could be solved with the use of simulation techniques, which are appearing during building and expansion of production halls and implementation of changes in planning workplaces resulting from e.g. new product manufacturing commencement – figure 37.

Analyses concern:

- production programs (scenarios) for various volumes (number of items) and structure (product structure).
- tracking of throughput limits,
- reached utilisation degree of production workplaces examination,
- resources congestion analysis (observation of queues length build up) [38].

Assignment of the above problem complexes to broadly known general planning phases of production systems shows, that by means of simulation techniques it is possible to elaborate a factory design taking into account its size and the topology of means of production.

It was observed, that between small, medium and large size enterprises differences exist in problems that simulation techniques are intended to solve and in expected outcomes and objectives. Definition and mixing of essential from the product structure market's point of view in the production system is the main objective of MSP simulation, whereas in large size production factories dominant are material flow, organisational structure and equipment structure optimisation – table 7.

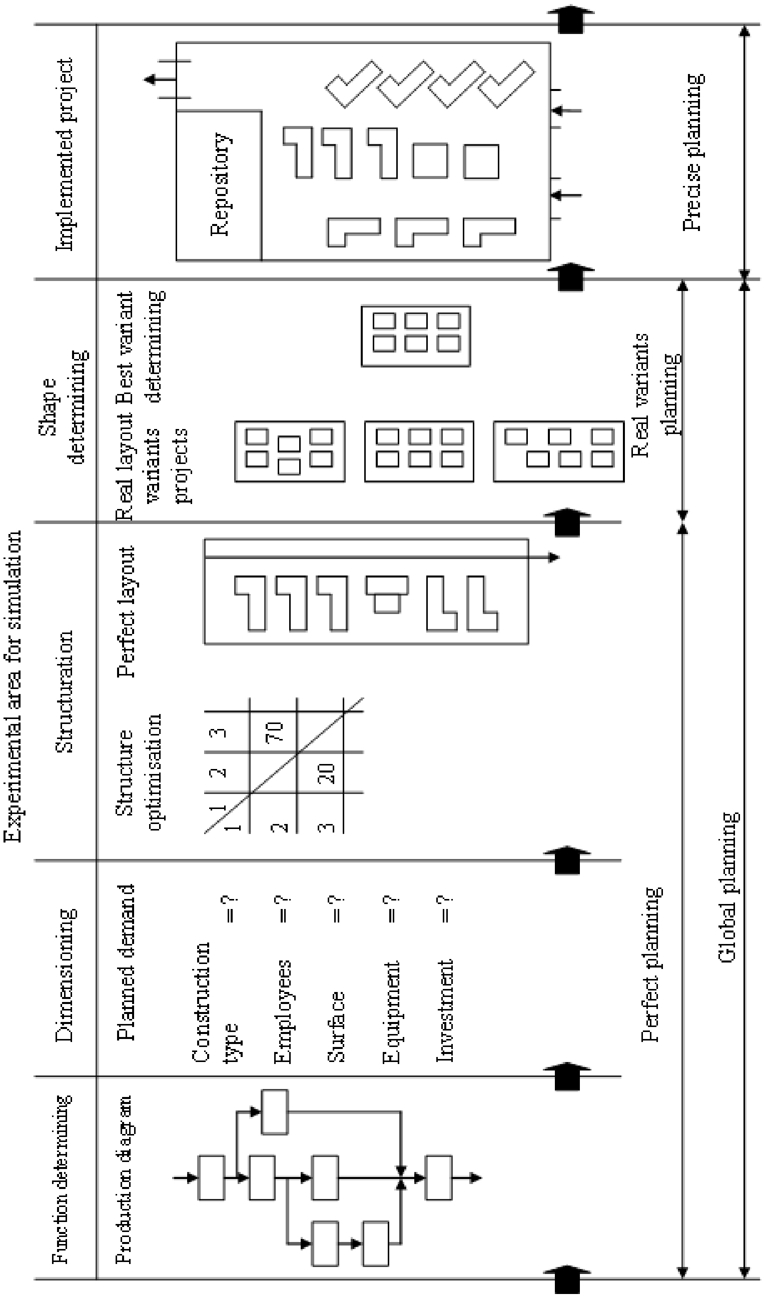
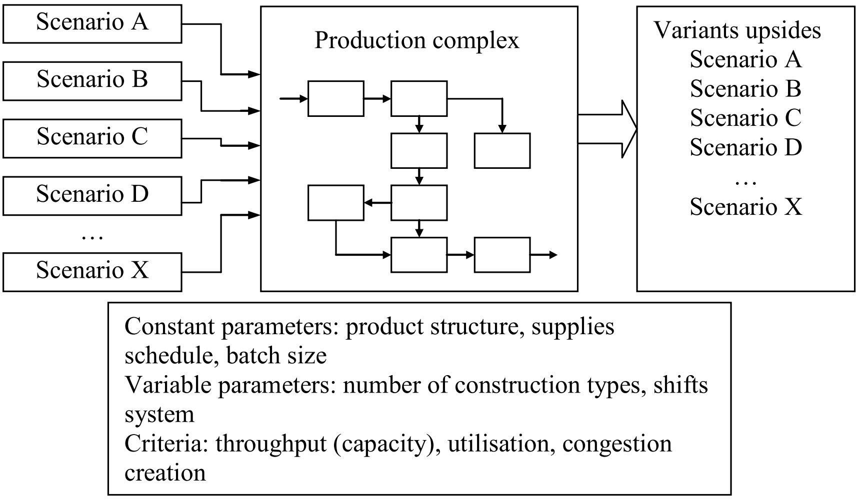


Fig. 37. Essential simulation functions in the systematic of factory planning [37]

Table 7. Differences in problems and objectives of a simulation analysis in small and medium size enterprises [39]

	Small and medium size enterprises	Large enterprises
Problem area (usually)	Product range and production system – small, Basic product flow (high transparency), Input and output product streams almost unknown (described)	Product range and production system – large Complicated product flow (low transparency), Input and output product streams relatively well known
Research objective (usually)	Optimisation of (turbulent) product streams (remaining in mutual relations) in the production system	Production system optimisation whilst maintaining unchanged product stream

One of ranges of features, which are provided by employing simulation techniques, is the comparison of variants differentiated by their parameters, which are subject to optimisation i.e. parameters, which in one of the models are constant, in the other variable and the other way round. The necessary condition for comparing those two variants is the maintaining of unaltered comparing criteria. Exemplary variants used during designing a industrial plant are adjusting production capacity of the facility to a production plan (figure 38) or production plan to the production capacity (figure 39).



Constant parameters: product structure, supplies schedule, batch size
Variable parameters: number of construction types, shifts system
Criteria: throughput (capacity), utilisation, congestion creation

Fig. 38. Scenario for realisation: adjusting production capacities of production facilities in accordance with the production program [39]

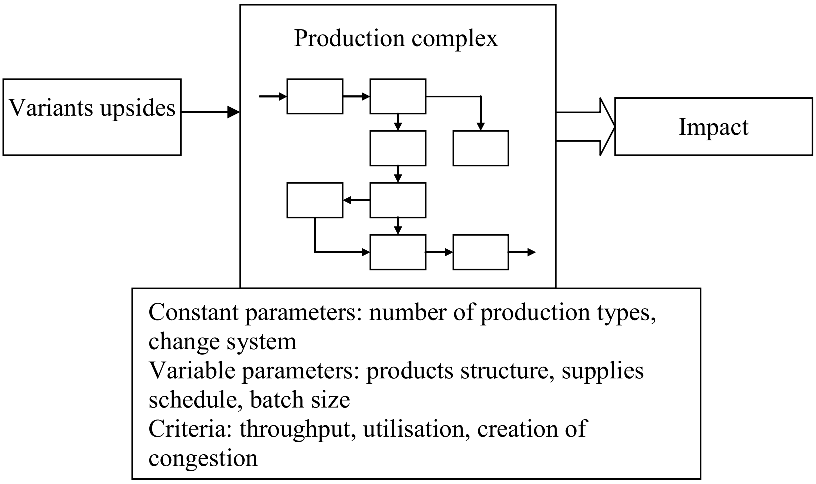


Fig. 39. Scenario for realisation: adjusting of production program to production capabilities of the facility [39]

3.6. Proceedings during simulation project realisation

This chapter is dedicated to the methodology of computer simulation, according to the current knowledge state. It includes the description of the correct procedure regulating the rendering of a process simulation (compilation based on the work [75], which in a precise manner reflects the state of knowledge on this subject – further [2], [3], [4], [5], [6], [7], [8], [9]). Essentially it boils down to eight fundamental phases, which are:

Step 1. Problem definition
Step 2. Design of an analysis
Step 3. Conceptual design of a model
Step 4. Formulation of input data, assumptions and definition
Step 5. Building, correction and approval of a simulation model
Step 6. Experiment conducting upon a model
Step 7. Document drawing and results presentation
Step 8. Definition of cycle durability model

Hereunder, is presented in a step by step fashion a detailed description of proceeding at consecutive stages of simulation modelling of an examined phenomenon, additionally presented in figure 40.

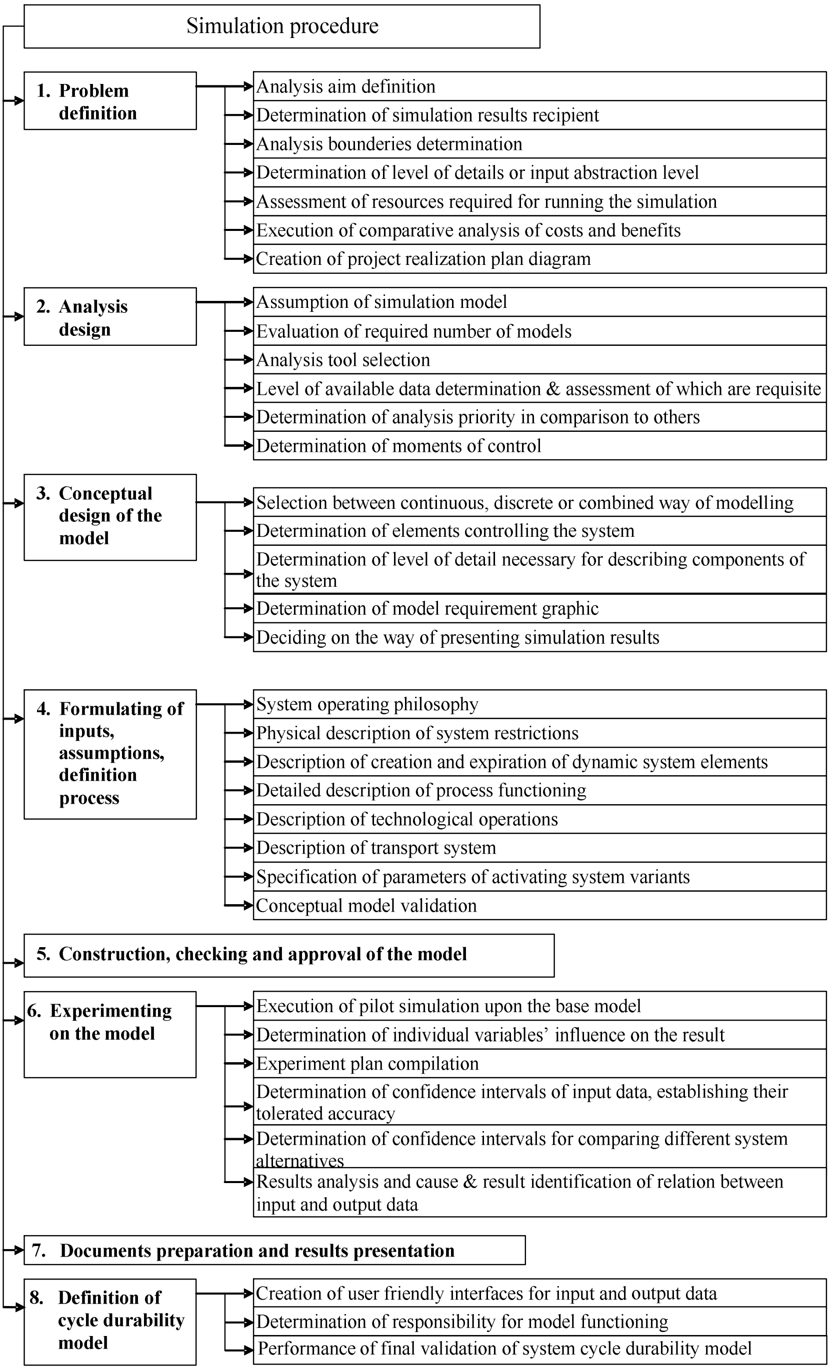


Fig. 40. Methodology of simulative proceedings (based on [75])

The course of construction, and subsequently execution of a simulation by means of the created process or phenomenon model, amounts actually to the successive performance of above presented phases. In practise often though, mainly due to the complexity of a modelled problem, there is a need of reverting to certain, beforehand carried out activities. It refers in particular to phases from 3 to 6 of the simulation process, e.g. the course of action associated with it may be frequently repeated, e.g. for an every alternative project part.

Phase 1. Problem definition

This process phase of creating a simulation model influences to the largest extent the final effect of the entire simulation. Incorrect problem definition may cause, that despite the sacrificed time and cost expenditure for a project realisation, its effects can prove to be useless or even detrimental.

The analysed problem should be clearly and precisely defined or documented.

Phase 1 connects to the following steps of proceeding:

Step 1. Analysis goal defining,
Step 2. Determination of simulation results recipient,
Step 3. Analysis boundaries determination,
Step 4. Determination of the level of detail or appropriate abstraction level,
Step 5. Evaluation of required resources needed for analysis execution,
Step 6. Carrying out of comparative analysis of costs and benefits,
Step 7. Creation of project realisation plan diagram.

Gathered after this phase's end information, should allow for assessment of the total cost of conducting the intended simulation experiment. A person or a group responsible for producing the simulation and a recipient, who is going to use its final results, should beforehand of proceeding with subsequent activities, meet up in order to accumulate and correct above information. That phase should conclude with a written formulation of all necessary inferences and information, which ought to be enclosed to project documentation.

Phase 2. Analysis project

Analysis project is the second, larger phase of the simulation process. At this stage of proceedings, some of described steps of preceding phase are examined to finer details, greater emphasis is also put on technical aspects of the problem.

In this phase there are the following steps:

Step 1. Assumptions of the simulation model,
Step 2. Assessment of the number of required models,
Step 3. Choice of examination tool,
Step 4. Determination of the level of accessible data and appraisal, which of them are required,
Step 5. Determination of a given analysis's priority against other,
Step 6. Determination of control moments.

Any information and documents created at this phase in the process of simulation should be enclosed to project documentation. Within this phase, based on new information available, people dealing with the simulation can introduce changes of project realisation time and required resources.

Phase 3. Conceptual project of the model

Determination of modelling strategy, which is going to be used in the analysis, is the third phase of simulation process.

This phase involves the following guidelines:

Step 1. Choice between continuous, discrete or combined way of modelling,
Step 2. Determination of elements controlling the system,
Step 3. Determination of the detail level, needed for describing system ingredients,
Step 4. Determination of model requirements graphics,
Step 5. Decision about the way of presenting the experiment's outcomes,
Step 6. Choice between continuous, discrete or combined way of modelling.

At this stage the person realising the simulation project faces the challenge of choosing the way of modelling. There are plentiful factors influencing the choice, such as analysis goal, detailed level of customer requirements and what's the most important, the character of events taking place in the real system.

Phase 4. Formulation of entries, assumptions, the process of definition

During phase five one should deal with a detailed description of system's operating logic, final required data accumulation for its modelling and task analysis. Within this stage the following steps are distinguished:

Step 1. System operating philosophy,
Step 2. Physical description of system restrictions,
Step 3. Description of creation and expiration of dynamic system elements,
Step 4. Detailed description of process functioning,
Step 5. Description of technological operations,
Step 6. Description of transport system,
Step 7. Specification of parameters of simulation variants' activation,
Step 8. Validation of conceptual model.

Information garnered at this project phase constitutes supplementation of so far gathered information. They are based on the previous stage (phase 4) identifying conceptual model area, specifying information necessary for its correct construction.

In the below figure 41 is presented the relationship between the control, conceptual and operational model validation. Rigorous procedures of validation for the conceptual model are equally important as control and operational validation, because executed earlier than others allow for time economy and correct action directing of people realising the entrusted them simulation project.

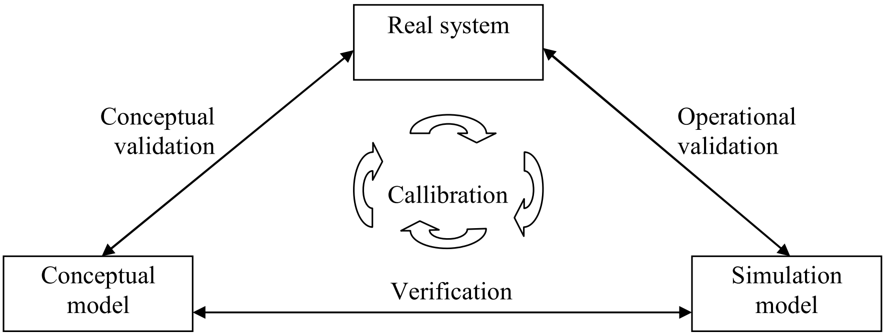


Fig. 41. Dependency between control and conceptual and operational validation of a model [75]

Phase 5. Construction, checking and acceptation of a simulation model

Model construction, its checking and operational validation constitute the sixth phase of the simulation process. During it, by using preselected specialised software a system model is created, validated and any necessary verification is conducted. At this stage we are looking at about thirty-forty percent of time stipulated for the simulation. This phase should be repeated for every variant of the model, base to start with to ultimately end up with the latest version of the task in hand. With those activities is very often connected the necessity of consult the proceedings and effects of actions with engineers and managers dealing with functioning of the real system as well as with people interested in results of the experiment.

The technique itself, of creating simulation models, their control and verification is predominantly reliant on the type of used simulation software. Specification of this tool employed in this process seemingly spontaneously imposes the mode and procedures of proceeding during the process. Utilised in this case simulation device should be optimum in respect of fulfilling all posed criteria resulting from the presented below methodology of its selection.

Received at the end of this process phase model is ready for realising through it, experiments planned for the subsequent research stage. During performed activities at this level, people dealing with a given simulation project can make decisions and take actions, aimed at aggregating a greater number and/or more detailed input data utilised for model calibration.

Phase 6. Conducting the experiment upon the model

Performing experiments upon the constructed system model and using related to the project certain experimentation techniques are creating the seventh phase of the simulation process.

During it, apart from the base model, research is conducted upon resulting from assumed parameters, its all other variants, on each occasion reverting to previous process phases if any significant changes took place. During this stage, instead of creating projects of experiments for the entire simulative analysis, generally bigger variables are identified and those of the smallest influence on the course and analysis result are eliminated. For variables of vital influence on result of the experiment, the analysis can be carried out with greater attention to details.

During those works, when the majority of results is available, persons dealing with the simulation are meeting the client, who on a regular basis can familiarise himself with it and determine new parameters' values, later examined by means of the model. He can present, which additional data are of interest to him, how the behavioural characteristic of the simulated system should look like.

Individual steps of this phase are the following:

Step 1. Making a pilot simulation of the base model, in order to screen to catch all irregularities and indications of potential errors for correction,

Step 2. Determination of the influence of individual variables on the result, omission where possible and accepted by client, those of insignificant influence on the experiment result,

Step 3. Elaboration of the experiment plan,

Step 4. Determination of confidence intervals for input data and deciding on their tolerated accuracy,

Step 5. Determination of confidence intervals for comparison of different system alternatives,

Step 6. Results analysis and identification of causes and results of relations between input and output data.

Phase 7. Documents production and results presentation

Documentation of a research project and presentation of its upshots has got a substantial significance for the success of the simulation experiment. The seventh phase generates the following set of documents depicting the course and the aftermath of the entire simulation project:

- project paper,
- model input and output data documentation and its code,
- system functioning project,
- user guide,
- modelling manual,
- recommendation for further research areas,
- project final report.

The majority of tasks in this phase are made concurrently with the steps of other key process stages, which should be reflected in the documentation and should be executed even when the client is not interested in its description.

Project paper

It is a specific kind of a document – a folder, whose task is to store all related to the research project information and data and to accumulate it in course of its realisation. The project paper can come in handy, in case of e.g. client wanting additional analyses and examinations related to the project to be run. It can also become a source of valuable information, which might prove to be helpful in case of realising other similar research projects.

Model input and output data documentation and its code

That documentation should be elaborated in a comprehensible and readable for client form, thus it cannot include excessive amounts of professional terminology from the field of simulation. That paper depicts, in a possibly simplified form, categories of input data and the way of implementing them, obtained output data (described at different detail levels). Moreover this documentation is supplemented by an enclosed record of the way a model was coded along with the attachment explaining used terminology.

System functioning project

This document is started to be elaborated at the end of the second phase of project realisation, then the information included in it, should present the way the real system is perceived by the persons responsible for construction of the simulation model. It allows for control and correction of possible misinterpretation of processes taking place in the actual system. In phases 3 and 4 of the analysis, report is successively complemented by detailed system information, i.e. data thanks to which this becomes a form of a user guide describing the process of model development.

User guide

It is a document serving as a manual. It comes as an aid for the user wanting to personally conduct research experiments. It includes a description, step by step, what activities should be performed, in order to carry out correctly the experiment by means of the created model. Specified in this paper is the register of parameters, whose values can be altered, which input data are necessary, of which type results are obtained and how should they be properly interpreted.

Modelling manual

It constitutes a form of help for people dealing with simulation and model construction. That document includes a detailed explanation of the way a model is coded, logic of its operating and construction. This description will come in handy in the future, when there would be a need of modifying or creating a similar model.

Recommendation for further research areas

When deploying the simulation methodology at problem solving, one acquires the knowledge of interdependency between operational processes taking place within a system. It allows for drawing conclusions on the subject of their improvement. Those establishments should be compiled and presented to the client. This document contains a set of premises and recommendations for conducting further simulation projects connected to the system. It determines the issues of probable future analyses and their aims.

Project final report

It is a document concluding the entire carried out analysis. That report shall incorporate the following elements:

- introduction,
- research scope,
- model assumptions,
- input data description,
- output data description,
- description of base model and results of its simulation,
- description of consecutive model variants and their outcomes,
- results comparison,
- inferences and propositions.

Phase 8. Definition of cycle durability model

Tasks related to creation of the cycle durability model constitute the ninth, final phase of the simulation process. This stage is applicable to long-term simulation research of system cycle durability. On the other hand, short-term simulation experiments are those, whose results are employed in the decision making process only the once. Their models are no longer in any way used by the client. Currently, from sixty to seventy percent of experiments can be classifies as short-term.

Long-term cycle durability models, are used predominantly as a tool for training and familiarisation of the client's staff with the system. Second purpose is their utilisation for determining - through simulation – the best way of using resources or organising their distribution. In that case they are used for manipulation of parameters characterising processes taking place in a system, without modifying their character (e.g. product mixing, alteration of batch size) and observation of their influence on realisation of those processes.

Construction of models of that kind requires additional tasks, which are characterised in the following steps:

Step 1. Creation of user-friendly interfaces of input and output data, Step 2. Determination of responsibility for model functioning,

Step 3. Execution of final validation of system cycle durability model.

3.7. Procedure of data gathering

In a simulation project data gathering and analysis in order to perform "cognitive process reproduction" is almost always the most difficult and the longest task. Recognition of what data are going to be needed for model building and determination of who is going to be responsible for accumulating them, constitutes the very basis of this stage. If a given person is accountable for data gathering it is important, that he would have a good rapport with people authorised to access them: engineers, technicians, managers or even clients.

Data gathering process involves the following steps:

- required data determination,
- data source determination,
- data gathering.

Determination of required data

In this step it should be determined which information from the actual system are necessary in the simulation model. Good method for identifying that information is to compile a list of real system constituents and subsequently screening for selection of the ones needed in the model. Every ingredient included in the simulation model, having a direct and indirect influence on result of modelling, should be approved by persons responsible for the project. Data accumulated from the actual system can be divided into three groups:

- Structural data. Structural data refer to all modelled objects, being elements (processed items), resources (transportation trolleys), localisations (storehouses, machines, buffers). Structural information describes in essence the model structure and its configuration and objects, which are influenced by processes occurring in the system.
- Operational data. Operational data explain how a system operates, i.e. when, where and which events are appearing in the system. Those data are consisting in logic and behavioural system information such as routes, schedules or resources allocation. Operational information is very easily determinable, provided that a process is structuralised and kept under control.

- Numeric data. Are providing quantitative information on the system. Exemplary numeric data contain capacities of buffers, storage areas, processing times or times of elements appearing in the system

When determining the data it is worthwhile to prepare a questionnaire containing the following questions:

- Which types of elements are subjected to processes in the system?
- What are the routes of elements flowing through the system?
- Where, when and in what quantities elements are entering the system?
- What are processes' times?
- Which resources are required for process execution?
- What are transport quantities of elements?
- On what basis resources (machines and devices) are designating the work order?
- What are the alternative decisions of choosing element flow routes through the system?
- How frequently pauses are appearing (tooling times, repairs) and which resources and times are demanded upon the occurrence?
- Is there a possibility of defining pauses for resources?[40]

Answers to all those questions should provide all or almost all information required to build a model. Depending on the system and detail level that questionnaire can be updated with successively added questions.

Determination of data sources

The type of data source is reliant largely on the fact, whether the model is being built on the basis of an existent system or a designed one. Quantity of data sources for existent systems is very high. As sources, historic information can serve or people holding knowledge about a production system. The sole fact, that a system exists, allows for a personal observation, therefore one can be less dependent on data from other sources, however cooperation when gathering data is always recommended. For systems being designed, data sources are usually limited to people directly engaged in designing the system. Typical data sources for building a model are:

- class MRP, MRP II, ERP systems,
- class PDM, CAPP, SFC, PPC systems,
- CAD systems,

and

- constructors,
- technologists,
- supervisors and workers of a production line,
- employees of logistics, purchases and sales departments,
- Top Management.

From those sources are acquired data regarding facility development plans, sales plans, final product structure and technological processes for components manufactured in the facility, details of handling workplaces and so on. Methods of registering the data are shown in figure 42.

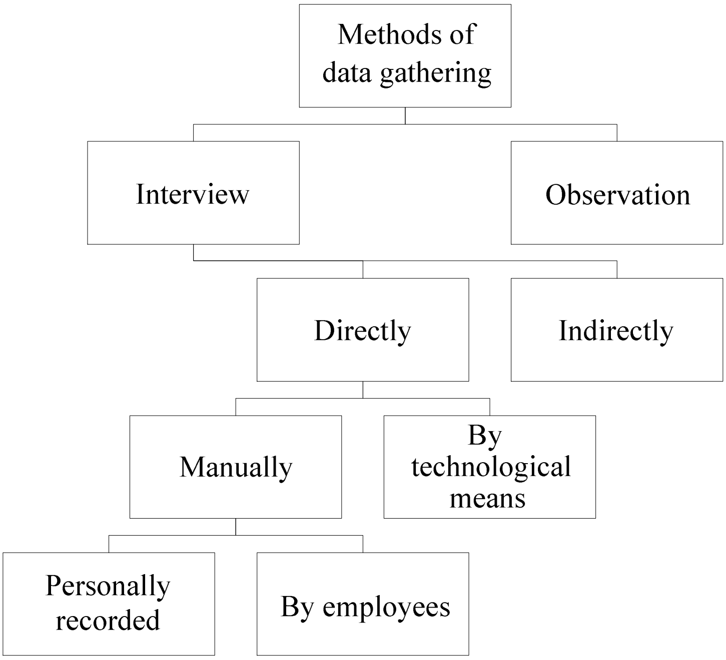


Fig. 42. Methods of data gathering. Own development based on [53], [54], [36]

In case of direct registration, data is accumulated in places of its creation. Usually it takes place at a workplace. With this way of collecting data, data forging can be excluded, however it burdens staff with additional work. Personal data gathering causes extension of the simulation project running time, but it facilitates better familiarisation with the manufacturing system.

Data gathering

In practice data gathering lasts from the very beginning to the very end of the simulation project running. This is because, some information can be available in the very moment a corresponding requirement occurs whilst other demand time, in order to properly prepare and process them. Data should be collected in the following order:

- determination of elements flow through the system,
- operation description preparation.

A facility management on the basis of a production plan – in industrial verification examples with use of Pareto analysis – a list of products is determined, which are intended to be featured in the model. Production process description for chosen elements is compiled in a narrative form or in form of a table, in order to document the way of their modelling. A proposed template of such Simulation Card is shown in figure 43. Regardless of the form, a description should include:

- time and resources needed for executing an activity or an operation,
- place, time and quantity of moveable elements from localisation to another,
- time and resources needed for moving element to a next localisation.

Ordinal number	**Item**	**Description**	**INPUT Buffer seize**	**Type of INPUT containter**	**INPUT container capacity**	**Station, cell**	**OUTPUT buffer size**	**Type of OUTPUT container**	**OUTPUT container capacity**	**Description**	**Operation time (t_{pz}, t_j) in cell [Min]**	**Setup time [Min]**

Fig. 43. Simulation Card template – for collecting data on the movement of material [73]

When building a model the data contained within the structure and technology of chosen products are utilised. In order to systemise the knowledge on the subject of production processes, one can elaborate diagrams of functions, flow of materials of individual elements according to modelling technique rules: EXPRESS, IDEF, SA, MOSYS, CIMOSA and others. Elaborated diagrams allow for better familiarisation with production processes of particular elements, hence aiding the process of building a simulation model and they increase the accuracy and credibility of obtained information about the production process realisation. Additionally during realisation of the simulation project the IDEF0 technique can be utilised for process modelling, which is relatively easy in application and widely described in available literature [46], [59], [66], [60], [65].

3.8. Optimisation of a simulation project

Optimisation (Latin) a mathematical issue of finding the best solution (in terms of a predetermined criterion) from a set of feasible solutions; static and dynamic optimisation are distinguished; employed e.g. in automatics (optimisation of production process control).

The author proposes the following division of planning problems optimisation in production management systems:

- direct optimisation:
  - mathematical solution of a problem in form of fitting an existent optimisation algorithm (for a given problem class) or developing a special algorithm for a particular problem,
  - real process experiments,
- indirect optimisation – simulation of processes, by means of applying simulation suites:
  - processing and conducting a simulation experiment (DoE) and statistical analysis of its results,
  - creation and testing of “what-if” scenarios until achieving a satisfactory result.

3.8.1. Direct optimisation

Every solution of an optimisation problem, which is using a real object or its deterministic mathematical model (for which there is an appropriate method of discrete optimisation) is going to be referred to as direct optimisation. Below is an approximate mathematical solution of planning and control problems in discrete production management systems. Descriptions of reaching an optimum solution by changes in the actual system and results observation were omitted, due to obviously high costs of such a method.

Mathematical discrete or discrete-continuous optimisation belongs to the class of especially inconvenient from the calculation's point of view problems. Problems of discrete optimisation can be written in form of a minimisation task of a certain function [24]:

$$\min_{x \in X} K(x) \tag{9}$$

where:

K (x) – objective function,

X – a set of feasible solutions defined by the set of restraining conditions

Main reasons of calculative problems are [24]:

- frequent lack of "classic", analytic properties (differentiability, linearity and so on),
- multi-extremes presence with a substantial number of local extremes,
- NP-hardship of the majority of problems originating in the practice,
- The "curse" of multidimensionality.

The consequence of the above problems is the fact, that taking into account the degree of real optimisation tasks' complexity, solution of a practical task requires sometimes hundreds of thousands of years of the most contemporary computers. (as an example let's take the SETI project, whose solution was being searched by thousands of private computers when a special screensaver was activated).

Basic concepts of computational complexity theory

The fundamental question when solving problems of combinatory nature is either existence or non-existence of an algorithm capable of solving a given problem [26]. In case, when an appropriate algorithm exists, then the problem is theoretically solvable. Theoretically, because a particular algorithm might not lead to a solution within a reasonable timeframe and with a sensible occupation of computer systems' memory. In considering the issue from the time of solution's point of view, we can distinguish algorithms easy and difficult computations-wise.

Below are presented shortened elementary definitions of so called decision problems class, so ones which give the answer of "yes" or "no" to a posed question. The optimisation then, is conducted by finding an extreme of a certain function, but with every optimisation problem we can associate a corresponding decisional problem in form of an answer to the question of: whether there is a solution with the value of objective function not greater or no less than a certain, pre-established constant. A problem posed in this manner has got very similar (computationally) properties as the optimisation problem itself [26].

"By a decision problem (DP) we understand a set of defined parameters (a class) and a question to which the answer is either "yes" or "no". After determining values of all parameters of a given DP we get a particular problem (an object), which is denoted by the *I* symbol, and the set of all *I* objects for the *DP* class is denoted by $D_{DP.}$ Data of the $I \in D_{PD}$ is recorded by a finite *x(I)* string of symbols with accordance to the predetermined record rule. The size of *I* object is the length of the data string denoted by the symbol *N(I)*"

"The function of time computational complexity of an algorithm *A*, completing the *DP* class is a function assigning to an every value of *N(I)* size of an $I \in D_{PD}$ object a maximum number of elementary steps of a digital machine needed for solving a particular problem of that size by means of an *A* algorithm" [45].

"Let's assume that the function *F(k)* is of an order *G(k)*, what we denote by *O(G(k))*, if there is a constant *c*, that $|F(k)| \leq c\ |G(k)|$ for all *k* values (where $|F(k)|$ denotes the absolute value of *F(k)*).

Assuming the above, by a polynomial algorithm we call an algorithm, whose function computational complexity is *O(p(k)),* where *p* is a certain polynomial, and *k* is the size of an actual object. Every algorithm, whose complexity function cannot be limited is such a way, we call an exponential algorithm (over-polynomial). Polynomial algorithms are treated as effective, whereas exponential as ineffective, from the computational complexity's point of view" [45]. Further definitions require introduction of the Turing machine concept.

Deterministic single-taped Turing machine (DTM)) is defined as an abstract machine equipped in a single-sided infinite tape, on which by means of a head one can read and write symbols from a certain alphabet [12], [66].

Non-deterministic, single-taped Turing machine (NDTM) consists of DTM and a generating module [12]. Execution of the

NDTM program is different to DTM (despite the program itself is identical). Initially, the generator writes on the type in a random manner a string of *S*-symbols belonging to the machine's alphabet. Then NDTM checks, similarly to how the program is executed by DTM, whether the generated *S* string completes conditions determined in the *I* object query [45]. In other words DTM searches for a problem's solution by executing a program, whereas NDTM guesses the solution and tries to prove, that it satisfies conditions posed by the problem.

„We say that NDTM solves DP in (at the most) polynomial time, if for an every $I \in D_{PD}$ object, for which the answer is "yes", there will be generated such a *S* string, that the time of performing the generating stage and checking stage concluded by the "yes" answer by NDTM (for *I* and *S*) is $O(p(N(I)))$ for a certain *p* polynomial.

The **P** class is created by all DP, which in at the most polynomial time are solved by DTM, the **NP** class is created by DP, which in at the most polynomial time are solved by NDTM.

The transformation of a polynomial PD_2 problem into a PD_1 ($PD_2 \propto PD_1$) we call a function F$: D_{PD2} \rightarrow D_{PD1}$ which completes the following conditions:

- for an every $I_2 \in D_{PD2}$ object the answer is "yes", if and only if for the $F(I_2)$ answer is also "yes",
- the time of calculating the *F* function by the DTM for an every $I_2 \in D_{PD2}$ is restricted by the upper limit of the $N(I_2)$ polynomial.

We say, that DP_1 is **NP-complete**, if $PD_1 \in \boldsymbol{NP}$ and for every other $DP_2 \in \boldsymbol{NP}$, $PD_2 \propto PD_1$. Moreover, we say, that an optimisation problem is **NP-hard**, if the decision version corresponding to it is **NP-complete**" [45].

Discrete optimisation methods

As previously mentioned, every discrete optimisation problem can be written in form of a minimisation task (or maximisation) of certain functions. Exemplary forms of functions and optimisation criteria are presented in the paper [25].

Below are presented in a nutshell methods of a discrete optimisation.

All methods are divided into:

- accurate methods – finding globally optimum solutions for a given problem, and

- approximate methods – finding solutions close to globally optimum solutions. Of course, it needs to be taken into account, that the more accurate solution (closer to the globally optimum solution) the more costly computationally is the method giving such solutions.

In accurate methods we distinguish [24]:

- effective dedicated algorithms,
- methods based on the scheme of division and restrictions (B&B),
- methods based on the scheme of dynamic programming,
- methods based on integer programming,
- methods based on linear-binary programming,
- subgradient methods.

The first group of methods (effective algorithms) are recommended for solving particular problems in class P or NP-hard computational problems, the remaining methods are recommended for specific problems strongly NP-hard. There are significantly more approximate methods than accurate methods. Below are listed some of them [24]:

- construction algorithms,
- priority rules,
- adaptive search,
- local search,
- descending search,
- random search,
- threshold search,
- evolution search,
- AI methods,
- expert methods,
- multi-agent methods and so on.

Above methods utilise the latest achievements in the area of artificial intelligence, genetic algorithms, mathematical network models and so on in order to shorten as much as possible, the time required to obtain a “good” solution of an optimisation task.

3.8.2. Indirect optimisation

By an indirect optimisation we will understand the solution of an optimisation problem through using a model of an object different from a deterministic mathematical model, or a model for which there is no appropriate method of discrete optimisation (accurate or approximate). Optimisation of such a problem is going to be conducted using different types of computer simulation suits.

Methods of modelling and simulation of discrete processes (especially production processes) were adequately presented in previous chapters. The technical side of carrying out simulation analyses (methods and tools) is well described there, left for explanation is the practical way of solving optimisation problems by means of simulation tools. The square one for an every simulation is determining the aim of a simulation (determination of optimisation problem) and construction of a model adequate to a pre-established problem. In the majority of cases, when we seek for answers to concrete questions (and the upshot is either a “yes” or “no” answer), running a single simulation might be enough for obtaining that answer (e.g. is execution of that order possible in determined by the client time?). Unfortunately the profitability of creating a model for performing a single simulation is very doubtful (hence the need for developing a quick method of production processes modelling), therefore the effort of designing and conducting a simulation is made when the problem is difficult to solve with other methods (e.g. transportation system optimisation upon implementing into production a new product or upon a complete production change).

Depending on an employed simulation suite, two methods of solving an optimisation problem are applied. Utilising the built-in optimiser, or an outside connection of our tool with a statistical suite we can plan and execute the entire experiment (DoE) or solve the problem by using the “what-if” scenarios method – alteration of input values – simulation execution – analysis of changes’ influence on the system.

Optimisation method through “what-if” scenarios analysis

The method of analysing “what-if” scenarios is a standard optimisation method, used in discrete simulation suites. It is conducted by performing repeatedly a simulation with input parameters being altered each time (or an entire model) in order to observe changes’ effect on the model. In case when range of variability of an input parameter is substantial, or the quantity of parameters subject to change is significant, the method becomes rather laborious.

The effect of an optimisation is obtained by an appropriate selection of the parameters occurring in statistics being the result of a simulation (e.g. cycle, resources load, cost and so on) and an attempt of implementing such changes into input parameters in order for subsequent simulations to lead to maximisation (or minimisation) of an examined output parameter.

Some simulation suites [29] offer a software support in optimisation through the method of "what-if" scenarios by storing and presenting in reports results of all hitherto simulations (along with information on what has been altered). Nevertheless the method is recommended for solving straightforward (requiring a low number of simulations) problems, or for confirming (or overthrowing) previously putative solutions.

Optimisation method by experiment planning (DoE)

Some simulation suites have got an in-built optimiser, or they have an interface to an exterior optimisation program, thanks to which it is possible to design and perform an entire simulation experiment according to the methodology of DoE (Design of Experiment)

The beginnings of the DoE method reach the thirties of the last century, when an English mathematician sir Ronald Aylmer Fisher had started to explore the subject of experiment planning in conjunction with variation analysis. The novelty in his approach to the issue, was the change in priorities during the course of an experiment. Thus far experiments had been conducted first, and afterwards an investigation would normally brake out to established what has just been examined. Fisher's method assumed that first the aim of an analysis would be determined along with results analysis method, and subsequently how the experiment would be conducted and measurements taken [30]. The alteration in approach to experimental research fruited in several instant benefits:

- decrease of number of performed measurements within a single experiment,
- significant restriction of the possibility of incorrect examination results analysis,
- simpler and more comprehensive interpretation of test outcomes.

By using the DoE methodology an experiment can be planned in such a way, that by means of a minimum number of measurements one of three fundamental analysis aims can be achieved:

- verification of significance of input values $X_{(1)}...X_{(n)}$ influence on output values $Y_{(1)}...Y_{(n)}$,
- finding of extreme states of objects (optimisation),
- finding of an object function.

The last examination objective is the most extensive and includes the remaining two aims (if as a result of examination a function is obtained, afterwards through analytic methods its extremes can be found and we can describe the influence of individual input values on output).

The scheme of conducting an experiment with accordance with the DoE methodology includes:

- an object's characteristic (data gathering on the analysed object),
- research aim determination,
- choice of a research method,
- measurements realisation,
- results analysis,
- results documentation (conclusions from the experiment).

In the first stage we accumulate information on the subject of an object being subject to research. We determine input data, whose influence on output we are going to examine, and the scope of their changeability during the experiment. After determining the experiment's aim, we choose an appropriate experiment plan.

The most straightforward (while being the priciest time-wise) is a so called complete plan, where a measurement is taken for an every combination of input parameters. As easily seen, if the number of input variables equals n and each of variables takes k-values, then the number of measurements in the complete plan equals n^k.

During past few years many methods have been devised limiting the number of measurements being taken. Each of those methods is called a measurement plan. Due to the universality in experiment plans are used dimensionless, normalised values of input values from the interval of [-1, 1], which beforehand of measurements are converted into real values [30]. Large number of applicable measurement plans allows for selection of such a plan, which would provide finding of an object's function of a pre-established form and restrict the number of measurements down to a reasonable value.

Second important area in DoE methodology is the analysis of experiment's results. Conventionally it is called a statistical analysis and comprises:

- estimation of measurements' inaccuracy (together with errors of measurement methods and tools),
- object's function approximation,
- appraisal of compliance of found function with the experiment's results,
- finding object's extremes (optimisation).

Since R. A. Fisher mathematical apparatus comprising measurements' results analysis has substantially expanded [31], and computers allow for its practical application. Today virtually every spread sheet has got the majority of functions useful in statistical analysis, and specialised statistical suits (such like e.g. Statistica®, MiniTab®, and so on) are providing a complete tool for experiments planning according to the DoE methodology and its results analysis.

4. Tools for simulation – commercial systems

4.1. Ways of appraising and choosing simulation suites

In the market of simulation applications there have appeared a large number of computer simulation suites. Hence it is important, to correctly appraise quality of a simulation software, cost of the suite, installation and maintenance. Complexity of simulation suites requires expertise, in order to choose an adequate simulation suite. Decision making about purchasing software for simulation depends on identification of criteria and their significance in the decision model. Often such models are created in a hierarchical form starting from a general, rough aim determination, which with time becomes more definitive and broken down into sub-goals. Assessment and selection of simulation software is always time-consuming. The very first step in evaluating simulation suites is recognition and testing their abilities. Simulation appraising criteria can be found in articles dealing with this subject, experts' advice, companies' information materials, user guides and by working with simulation suites.

The progress in computer technology, changes in suites' features, various and imprecise terminology can hinder creation of a standard criteria list. But a dynamic list can be created with the possibility of making changes and adding new criteria, without any interference with the entire selection methodology [63], [5], [43], [62].

Criteria can be segregated into groups from three to eleven. If there is an excess of groups, it impedes determination of criteria for a single group, because a certain criterion might belong to several groups. If there are too little groups the selection will be insufficiently clear.

Software appraisal consists of seven main groups – figure 44. Criteria group **vendor** is connected with evaluation of credibility of the vendor and to some extent its software. One of more important sub-criteria are in this case vendor's brand, incorporating vendor's and its software history, documentation quality and offered technical support. Amongst criteria in **model and input data** group, are counted ways of building a model (ease of use, graphic interface), available modules and statistical distributions, queuing methods, possibility of automatic data gathering.

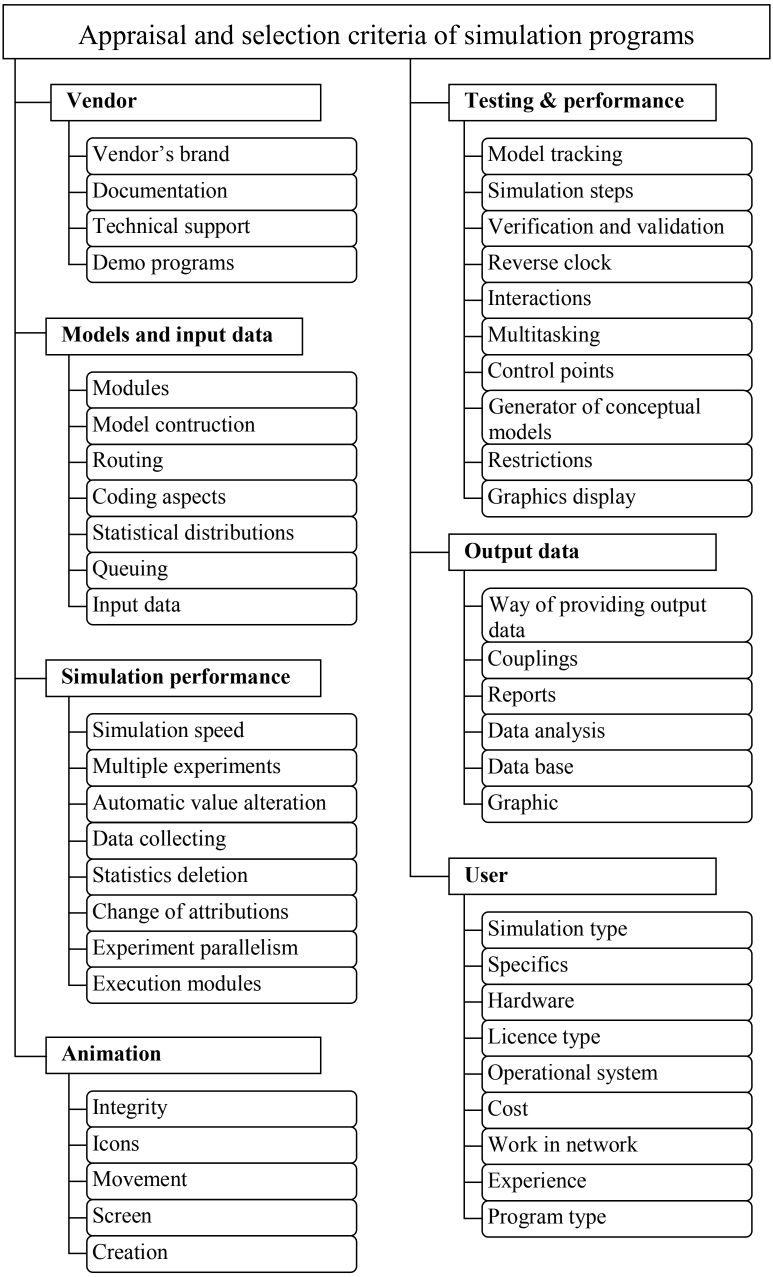


Fig. 44. Main criteria groups of appraising and selecting simulation programs, based on [63]

Criteria group **simulation execution** includes i.e. possibility of conducting multiple experiments, automatic values and attributes change. Criteria for **animation** feature assessment of creation, fluency and quality of animation. An important characteristic is the ability of using standard graphics libraries, creation of own ones by means of graphics editors and the possibility of importing them from CAD systems. Criteria group effectiveness is related to assessment of stability, error detection and software's performance. Aided validation and verification, multitasking, interactions, control points are the most essential from sub-criteria in this group.

An important feature, facilitating the appraisal and comparison of simulation suites are **input data** – types of generated reports, quality of included statistics, possibility of defining own reports, creating charts and histograms displayed dynamically during conducting of a statistical experiment. The last of criteria groups is connected with the user, owned by him experience, selection of simulation type (discrete or continuous), requirements regarding the availability of versions for run operating systems, types of licences and costs. The cost criteria is one of the most crucial criteria, simulation suite's cost is increased by the expenditure of purchase, installation and necessary trainings.

4.2. Digest of exemplary systems for modelling and simulation

Not that long ago simulation tools were perceived as dysfunctional when it came to designing production processes. Currently has emerged a number of new and easy-to-use tools with intended use of modelling and simulating discrete manufacturing processes. For that reason simulation is at the moment one of the most important tools for production planning in manufacturing enterprises. It allows for flexible adaptation to market needs and constant reduction of production costs.

In table 7 is presented the comparison of four simulation tools, belonging to the category of simulators. The programs are: Arena, Promodel, Corporate Modeler and iGrafx Process.

In figure 45 is presented classification of most frequently used – currently in the world – computer simulation systems [50], [14]. From the enterprise management needs' point of view with the greatest usefulness simulation systems are characterised, based on the concept of module graphic implementations.

Brought closer below are each and every of tools presented in the table 8.

Table 8. Comparison of several simulation tools belonging to simulators group

Simulation Suite	**ARENA**	**Promodel**	**Corporate Modeler**	**iGrafx**
Company	ROCKWELL SOFTWARE	PROMODEL Corp.	CASEWISE	COREL Corp.
Additional modules	MPSim: aids production modelling Preactor: scheduling BPSimulator: Business Process Reengineering	Changes: Work and breaks scheduling SimRunner: optimisation StatFit: statistical module	-	RapiDoE – Rapid Design of Experiment FitData – matching probability distribution with data Process Analyzer – SigSigma processes analyser
Manufacturing aiding modules	Material flow analysis Information flow analysis Load analysis	Material flow analysis Manufacturing system analysis	Material flow analysis, Information flow analysis Manufacturing system analysis	Material flow analysis, Information flow analysis Manufacturing system analysis
User interface	Tool bars, icons, dialog windows, 2-D animations	Tool bars, icons, dialog windows, 2-D and 3-D animations	Tool bars, icons, dialog windows, 2-D animations	Tool bars, icons, dialog windows, 2-D animations
Interfaces	ODBC, OLE, Visual Basic, data import from DXF format	OLE	OLE	OLE, data bases, MiniTab – statistical suite
Programming languages	SIMAN: simulation language Cinema: animation language	Script language	VBA	VBA
Reports	Automatically generated final statistics Statistical analysis of input and output data	Automatically generated final statistics and their processing in the statistical module	Automatically generated final statistics	Automatically generated final statistics Own reports defining
Extra functions	AST – exemplary Visual Basic solutions, on-line help	RTI – the runtime interface – experiment designing	Repository facilitating group work on projects	Repository facilitating group work on projects
Price	-	$13 000,00	-	$2 500,00

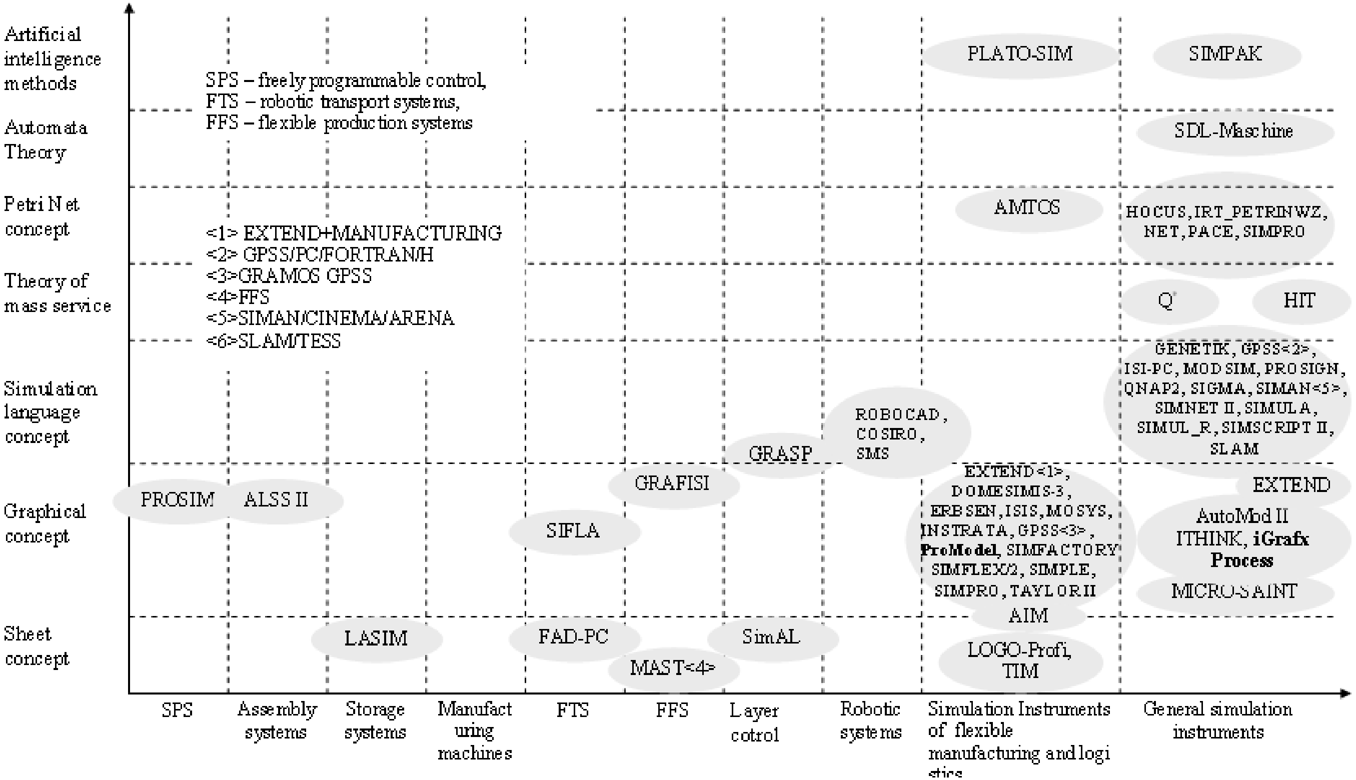


Fig. 45. Classification of currently mostly used in the world computer simulation systems [50], [14]

Simulators are perfectly suitable for building professional systems analysing production processes, due to optimum functionality both for the user as well as system designer (they are characterised by ease of use and great abilities in analysing simulation results and an elective expandability thanks to intrinsic programming languages).

4.2.1. Corporate Modeler

Corporate Modeler® is a product of active in the market since 1989 British company Casewise. The program is built out of modules using a common database where aggregated are all appearing in the model diagrams, objects and their attributes.

A process in Corporate Modeler is shown as sequence of activities initiated by events and concluding with a certain outcome. Organisational units are shown as rectangular fields, on which activities are put. It is possible to estimate for individual organisational units the cost absorbed by their functioning in a given time unit, as well as costs of individual activities.

The most important modules of Corporate Modeler are:

- Hierarchy Modeler – facilitates depiction of statistical dependencies between processes, organisational units, employees, information technologies,
- Process Dynamic Modeler – facilitates acquisition of processes in a dynamic way, joins actions taking place in the course of a process along with organisational units and localisations, where they are performed, allows also for conducting simulations,
- Data Flow Modeler – facilitates obtainment of information flow within an organisation by means of diagrams (Data Flow Diagram),
- Entity Modeler – facilitates designing structure of database systems,
- Generic Modeler – facilitates presentation of data from databases in form of a diagram in a graphical form predetermined by the user,
- Repository Explorer – facilitates easy access to data about diagrams, models and objects saved in a database, integrating at the same time remaining applications included in the suite.

Corporate Modeler suite has become increasingly a more complex tool aiding mapping and reorganisation of processes, implementation of information processes and ISO norms. Especially noteworthy is the degree to which modules constituting the suite are integrated and a successful interpretation of simulation issues and implementation of data required for its conducting.

4.2.2. Arena

Arena®, product of SimCorporation company, is an autonomous simulation suite, used to model and analyse processes taking place within a company. Comparison of current status “this is now” with the perfect state “should be” allows for taking the correct direction when introducing changes. Arena® presents a dynamic process in a hierarchic scheme of operation and information storing (data in spreadsheets). Arena® has got a built-in estimate (compiled based on actions) and a strong system for presenting data. Thanks to them, the program provides means necessary for forecasting changes’ influence and the possibility of choosing the best system configuration.

Through an independent methodology Arena® is effective when analysing:

- companies,
- production,
- service,
- other systems.

Common drivers for simulation – process dynamic visualisation, measurable costs, bottlenecks recognition and devices throughput – are without a shadow of a doubt exquisite in Arena® environment. Arena® without a problem utilises the existent information. A close integration of the suite with Visio allows for a broad access to models and modelling tools. By Arena® standards i.e. ActiveX, DAO interface and VBA, datasets can be transferred directly into a simulation model [33].

4.2.3. ProModel

ProModel suite from PROMODEL company is a simulation tool for appraising, planning and designing production, storehouses or other business operations. This easy-to-use tool allows for building a computer model and testing it in different scenarios in order to find the best solutions for increasing value in an organisation. ProModel has got at user’s disposal many tools for visualising, understanding and correcting a system.

A typical ProModel application includes:

- implementation of a production line,
- cycle reduction,
- throughput, analyses of efficiency and improvement,
- identifying and minimising bottlenecks and restrictions,
- resources allocation,
- possibility of investment decisions.

Characteristic features of ProModel suite:

- quick modelling with an easy-to-use interface,
- possibility of examining "what, if" speed scenarios, easily and risk-free,
- easy manipulation and analysis of data with a possibility of exporting outcomes to Microsoft® Excel,
- construction of basic graphical models for production, storehouses and transport,
- an accurate system of random variables by using almost 20 types of distribution or direct data import [70], [71].

4.2.4. iGrafx

iGrafx system, product of Corel company is a coherent system of diversified graphical tools dedicated to enterprises [24]. Graphics increases the effectiveness of communication by visualising the content. iGrafx system provides tools adequate to needs and capabilities for using them by particular users at an enterprise's level. Common base resources for all system elements in conjunction with common formats of graphic documents facilitates sharing graphics independently of application in which they were created (all applications of iGrafx system cooperate with each other at the integration level similarly to how MS Office applications do). Concurrently advanced, often unique functions included in modules dedicated to specialised users guarantee satisfaction of even the most sophisticated needs. iGrafx system components are intended for operating in a network and possess built-in mechanisms restricting administrators' work related to managing them [27].

iGrafx program is intended for aiding planning and creating work organisation in companies and enterprises. The program allows for process modelling by:

- their graphical visualisation,
- analysis and simulation of their course.

Simulation results are presented in reports taking into account various criteria e.g. time, costs, utilised resources.

Process modelling facilitates making right decisions, because allows for answering the following questions:

- How much time do an individual process stages take?
- What should be the schedule of individual activities?
- Where are located bottlenecks?
- What are required data (inputs) and results (outputs) of an activity?
- What is the availability and utilisation of resources (people, machines, devices)?
- What is the cost of processing a single transaction?

Thanks to that, a designer can:

- find and indicate what can be improved in work organisation,
- find and indicate mistakes before they occur in reality,
- compute statistics about work time, costs, resources utilisation.

Processes are reproduced in a very realistic fashion. It's possible to e.g.:

- determine a legitimate number of overtime hours,
- indicate National Holidays and bank holidays,
- assign certain actions to designated time points (e.g. machine maintenance on every Saturday),
- introduce probability of failure or indisposition of individual process participants.

Analysis and simulation analysis of processes' course along with a graphic representation of the scheme, can be saved in form of HTML and send out to all interested people via the company Intranet.

5. Description of construction of simulation models of a manufacturing system in the ProModel program

ProModel software suite is a system for simulating and optimising production systems of different types and magnitudes, which operates under Windows. As a discrete event simulator, ProModel is primarily intended for modelling discrete production systems, however it can also model continuous industrial processes. The system can be customised according to personal needs, thanks to extension of graphics libraries containing workplaces, production resources etc.

By simulating a production system one can: determine the effectiveness of intended investments, correctly establish required resources, decrease costs related to ineffective production resources utilisation, compare different production solutions etc.

Typical systems, which can be modelled by means of the ProModel system are: assembly lines, transportation lines, flexible industrial systems, workshops, JIT and KANBAN systems, supply and logistic chains.

ProModel facilitates model building without the knowledge of the internal programming language, but by means of a convenient, graphical user interface. After completing simulation, such data as e.g.: resources utilisation, efficiency and stock levels, are presented in tables and charts. The SimRunner optimisation module possesses the capability of generating and comparing alternative models and a comprehensive system analysis and their optimisation according to assumed criteria [70].

5.1. The procedure of building a new model

Construction of a simulation model in the ProModel 2002 environment consists of the following steps, corresponding to "modules" available under the Build menu:

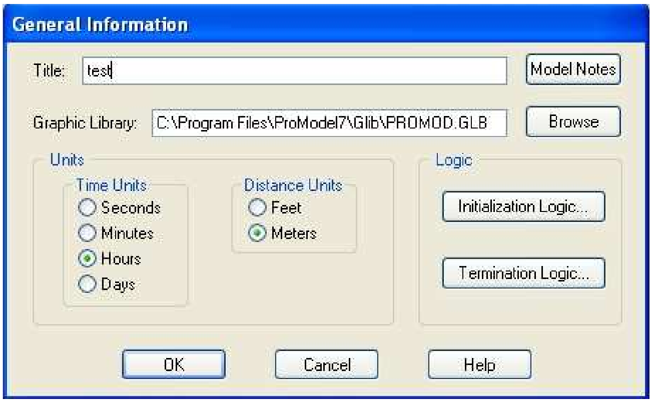
- device types selection, machines which will perform manufacturing processes (Locations),
- product definition (Entities),
- addition of work routes (Path Networks),
- determination of production resources (Resources),

- ➢ creation of process logic (Processing),
- ➢ product inflow schedule (Arrivals).

Those steps are indispensable when building the very first, basic simulation model of a manufacturing system.

5.1.1. Creating a new simulation model

Before creating a new model (figure 46), time units are ought to be determined [hours] and distances [metres] and graphical elements libraries selected (menu File/New/General Information). There is a possibility of introducing logic conditions, which would help to initiate and terminate the simulation process.



General Information

Title: test

Graphic Library: C:\Program Files\ProModel7\Glib\PROMOD.GLB

Units

Time Units

○ Seconds
○ Minutes
● Hours
○ Days

Distance Units

○ Feet
● Meters

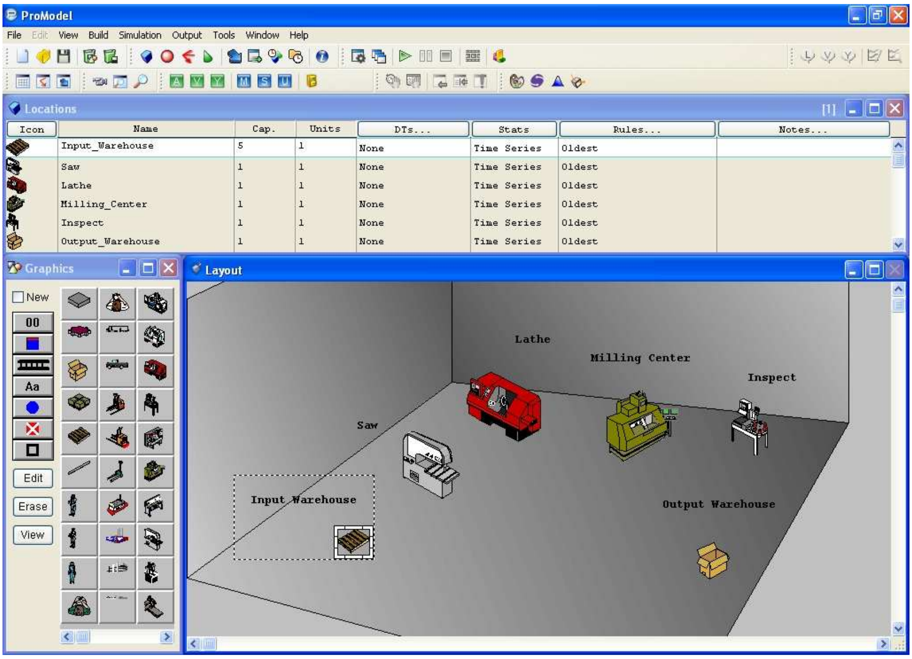
Logic

Fig. 46. Dialog box when opening a new model

The background, upon which the system is going to be built, can be created personally (menu Build/Background Graphics/Front of Grid or Build/Background Graphics/Behind Grid) or import a graphics file (Edit/Import Graphic). Acceptable formats of graphic files are: *.bmp, *.pcx, *.gif and *.wmf. One can use the available file named Tutorialback.wmf. After determining the grid's parameters (View/Layout Settings/Grid Settings) the proper model building can commence.

5.1.2. Locations module – workplaces

Locations module (figure 47) allows for the physical representation of a workstation, where technological operations and procedures will take place or decisions will be made. Workstations are situated in the simulation system by choosing them from the graphics menu and inserting into the Layout window. Distances between devices are defined in the following steps. It is possible to describe inserted devices with names of user's choosing, their editing and scaling. The graphic underlay can present e.g. the hall of a modelled system.



Icon	Name	Cap.	Units	DTs...	Stats	Rules...	Notes...
	Input_Warehouse	5	1	None	Time Series	Oldest	
	Saw	1	1	None	Time Series	Oldest	
	Lathe	1	1	None	Time Series	Oldest	
	Milling_Center	1	1	None	Time Series	Oldest	
	Inspect	1	1	None	Time Series	Oldest	
	Output_Warehouse	1	1	None	Time Series	Oldest	

Fig. 47. The Locations module window

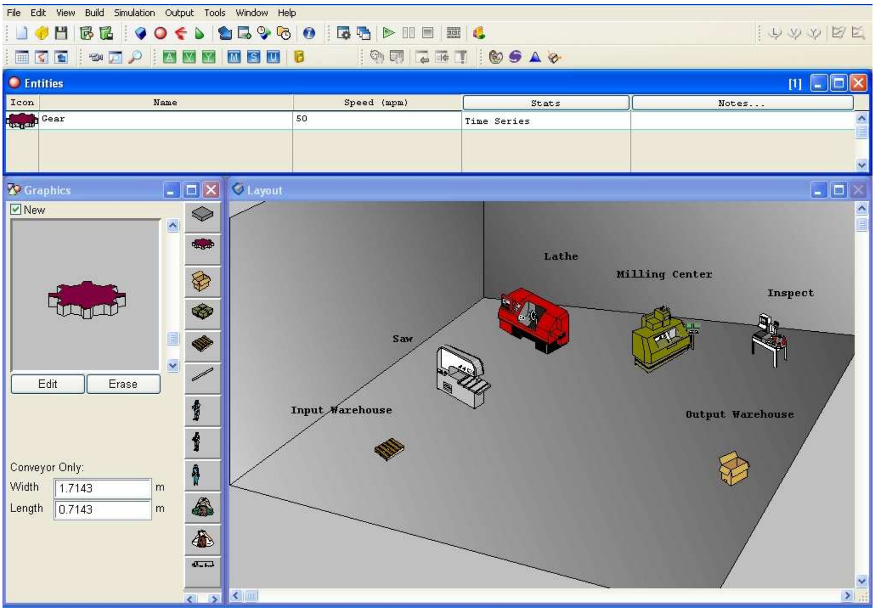
The graphical machines and devices library can be supplemented by user's own machines and devices, transportation means etc. via graphics editor (Graphics Editor).

Parameters defining the machines and devices inserted: Icon, Name, Capacity, Units, DTs, Stats, Rules, Notes are located in the Locations window. Option Icon presents an icon used for a graphical representation of a workstation during running of a simulation, column Name contains its name. Capacity allows for defining workplace capacities (understood as a quantity of items, which are simultaneously subject to manipulation). Option Units determines the number of identical workplaces, and Stats the type of generated statistic (Time Series is the most detailed statistics type). Using pause time editor and DTs exclusions facilitates determination of times and conditions, under which machines are temporarily switched off during the simulation. Occupying that gap could be defined setup times, using the t_{pz} (Setup downtimes) time, what is a certain simplification permissible during construction of a simulation model of a manufacturing system.

Definition of rules for input and output elements at workplaces, takes place in Rules option window. The following methods of selecting awaiting elements upon entrance are possible: priority oldest, random, lowest available performance, whereas upon exit one can set the following priorities: no queue, FIFO, LIFO, “after a type”.

5.1.3. Entities module – elements

Entities module – elements, which during the course of a simulation process are subject to activities or a decision made, so e.g. product part, part sets, products (figure 48). In this menu we determine elements, which are subject to transport and technological manipulations.



Icon	Name	Speed (mpm)	Stats	Notes...
	Gear	50	Time Series	

☑ New

Conveyor Only:
Width 1.7143 m
Length 0.7143 m

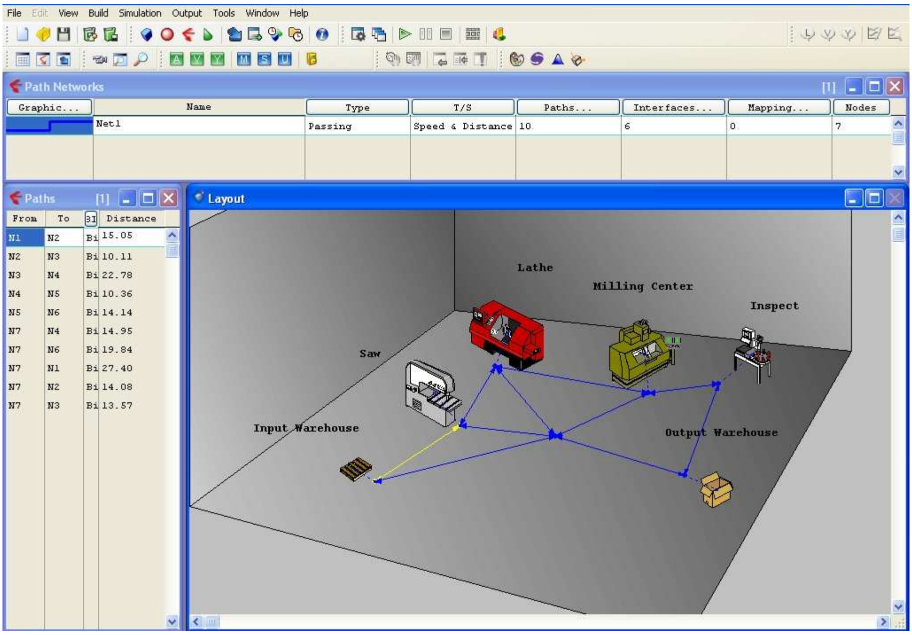
Fig. 48. The Entities module window

After choosing from a graphics library elements, there is a possibility of editing a chosen item and making changes e.g. of its size. Options defining brought in elements: Icon, Name, Speed, Stats, Notes. Options Icon and Name define unequivocally an element in the system, Speed – default speed, at which an element is going to be moved about (mpm – metres per minute, fpm – foots per minute).

5.1.4. Path Networks module – path, route

Path Network – a path (route), along which production resources are moving. Defining is done by a mouse, double-clicking creates subsequent network nodes (figure 49). Options for created network: Graphics, Name, Type, T/S, Path, Interfaces, Mapping, Nodes. For path identification in the simulation system is used the Graphics column (path colour) and Name. At the Type option we choose the type of a network being designed (Non–Passing, Passing, Crane), and in the T/S column a unit, which is assigned for traffic parameters on the network created. Devices' placement is entered from keyboard as individual distances between network nodes – Path option.

The next step is creation of interfaces between network nodes and individual manufacturing devices, by choosing the Interface option and clicking on a node and then a chosen workstation. Interfaces facilitate connection of network and devices situated in the modelled industrial hall. The Mapping option determines the movement order along the network and in its ramifications. Nodes facilitate determination of resources' number, which simultaneously can be present at a given node. If limiting the number of resources is not our priority – let us leave the field blank.



Graphic...	Name	Type	T/S	Paths...	Interfaces...	Mapping...	Nodes
	Net1	Passing	Speed & Distance	10	6	0	7

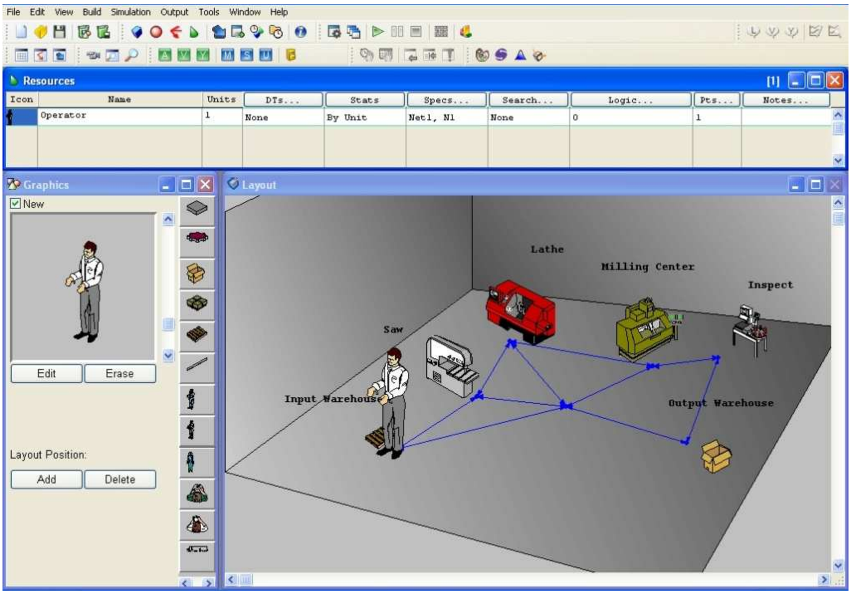
From	To	Bi	Distance
N1	N2	Bi	15.05
N2	N3	Bi	10.11
N3	N4	Bi	22.78
N4	N5	Bi	10.36
N5	N6	Bi	14.14
N7	N4	Bi	14.95
N7	N6	Bi	19.84
N7	N1	Bi	27.40
N7	N2	Bi	14.08
N7	N3	Bi	13.57

Fig. 49. The Path Networks module window

5.1.5. Resources module – resources, means

In this module we choose from the graphics menu production resources i.e. means of transport, workers or auxiliary tools and instruments (figure 50). Among means of production parameters are: Icon, Name, Units, DTs, Stats, Specs, Search, Logic, Points. Options Icon and Name allow for resources identification in the manufacturing system. The Units option shows the number of equivalent resources, pause time editor DTs allows for determination of time pauses for selected means of production. Stats facilitates the choice of created statistic (there are differences in the level of detail of – aggregated during the simulation – data regarding resources' behaviour).

The next step is adding a given mean of transport to the predetermined displacements network in the Specs window (Specifications). In it, we define the speed of movement of transport resources with a load or without it, acceleration, times of lifting and fastening transported items. The Search window facilitates choice of an optional search by means of transport for work or a parking space. The Logic option facilitates adding movement logic of resources in individual network nodes. By means of Pts (points) one can determine coordinates for the graphic representing the placement on the screen of production resources in the moment of their arrival at a certain node.



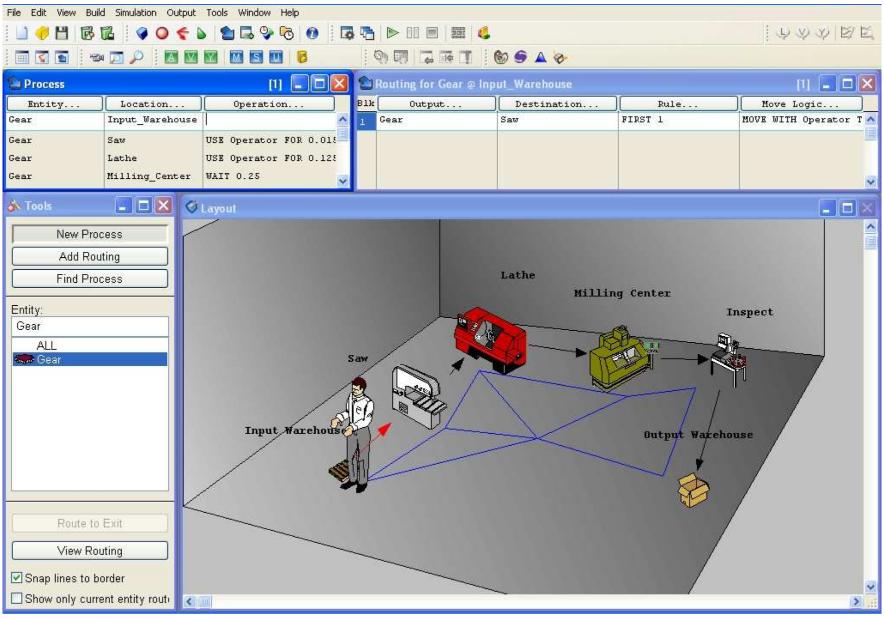
Icon	Name	Units	DTs...	Stats	Specs...	Search...	Logic...	Pts...	Notes...
	Operator	1	None	By Unit	Net1, N1	None	0	1	

Fig. 50. The Resources module window

5.1.6. Processing module – technological process

In the Processing module, operations are defined, which are taking place at a chosen workplace as well as production resources required for that operation (Figure 51). The next workplace needs to be indicated, to which there is a necessity of transporting the manufactured item.

The first step in describing technological processes is selecting in the Tools window an item, which will be subjected to processing processes. Next a workplace needs to be indicated (by clicking in the Layout window), at which a technological operation will be realised, then the place of a subsequent operation. In order to determine e.g. the time of conducting an operation or procedures, production resources needed for carrying them out you need to click the Operation... bar in the Processing window. To call out the command wizard, click the icon . In the command wizard we choose needed for process's realisation commands, in the next context window enter required parameters and attributes and paste in the obtained order form. After determining details of the modelled operation we need to define technological routes and establish the way of moving manufactured in the system elements and production resources. In order to do so, click the Move Logic... bar in the Routing for... window.



Entity...	Location...	Operation...
Gear	Input_Warehouse	
Gear	Saw	USE Operator FOR 0.01
Gear	Lathe	USE Operator FOR 0.12
Gear	Milling_Center	WAIT 0.25

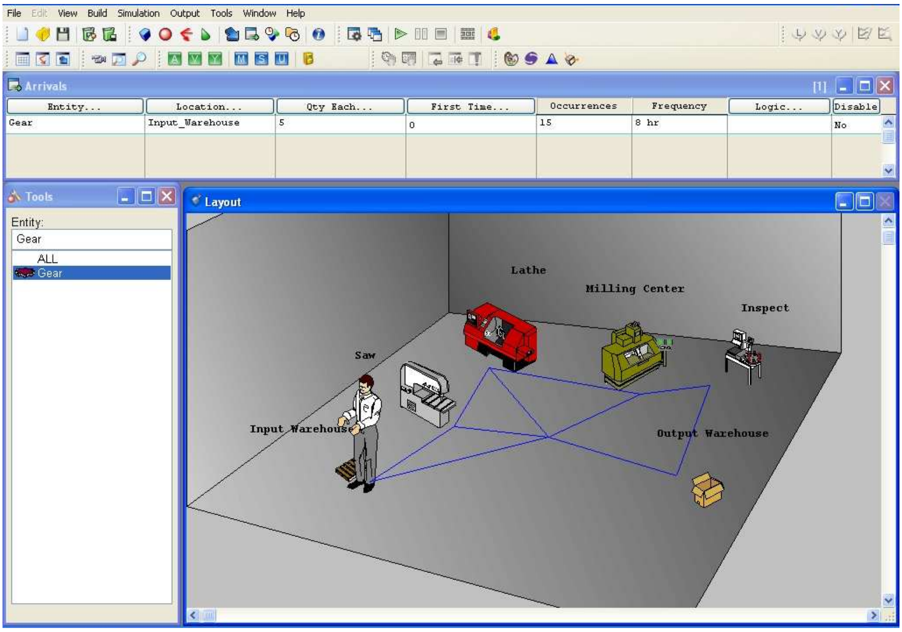
Blk	Output...	Destination...	Rule...	Move Logic...
1	Gear	Saw	FIRST 1	MOVE WITH Operator T

Fig. 51. The Processing module window

A window will open, in which we can type in a command or launch the command wizard, by clicking the icon. In the creator we select production resources and create the move logic, then we paste in the obtained command. Defining the end of the technological process requires – after the last operation – insertion in the Routing window, in the Destination field the expression: OUTPUT.

5.1.7. Arrivals module – delivery schedule

In this module we determine the delivery schedule for processed items (figure 52). First in the Tools window we choose an item, for which we are establishing delivery parameters at the system entry. By clicking the Location... bar we can determine the delivery place of a materials batch, Qty each... is the number of items in each batch, First time – time of the very first batch's arrival at the system entry, Occurrences – number of batches, Frequency – delivery frequency of material batches. The option Logic enables to add delivery conditions of consecutive batches of materials and items for processing, Disable – allows for suspension of material deliveries to the system.



Entity...	Location...	Qty Each...	First Time...	Occurrences	Frequency	Logic...	Disable
Gear	Input_Warehouse	5	0	15	8 hr		No

Entity:
Gear
ALL
Gear

Fig. 52. The Arrivals module window

ProModel includes also further additional elements used in expressions, which can serve to describe the logic of operations within the model. Those elements comprise variables, attributes, functions, user-defined distributions, costs. Similarly to main elements for modelling, additional elements' names cannot exceed 80 characters. The access menu to additional elements presents as follows:

Attributes – attributes, which are assigned to processed elements and workstations. They include such information as routing order, speed of processed elements, or number of a unit progressing through the system.

Variables – variables, are helpful in decision making and useful in statistical reports. A variable's value can be monitored throughout the entire time of the simulation course and is displayed at its end in form of e.g. histogram. Variables can be represented by integer or real numbers. Local variables may be utilised for defining swiftly the system logic.

Arrays – tables of variables of the same kind. Every array element works as a variable and can be referred to from every location were variables are in use. An array can be either one dimensional or multi-dimensional.

Macro is a complex expression, which can be defined only the once and used multiple times as a part of a logic expression. Macros are helpful, when the same piece of logic is being repeated is many places in the model.

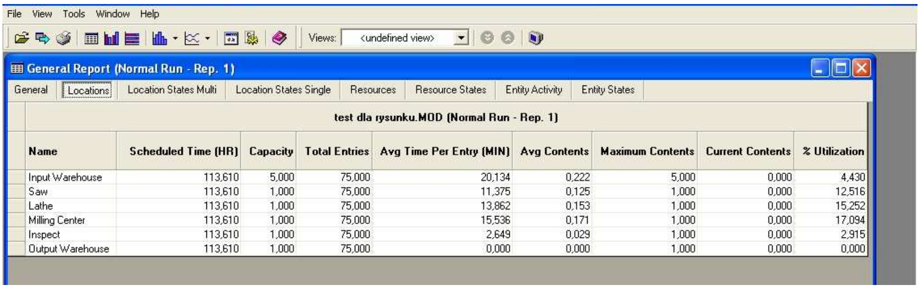
Subroutines are user-defined subprograms, which are used for executing the logic and they can yield values. They can be used in an every logic field. They are especially often utilised for building continuous models of manufacturing systems.

After defining the main model elements, such as: stations, resources, products, information about cost can be assigned (Build menu\Cost). Default displayed value is naught. The user is able to control costs related to a particular station, processed elements or resources over the course of the process. General statistical report contains cost statistics, being automatically gathered throughout the simulation. The user can find there, costs of:

- operating stations,
- operations at stations,
- the total cost of resources, containing the cost of resources consumption, unutilised resources and the total cost of processed elements including at least the initial cost of elements.

5.2. Simulation and animation

Model simulation can be conducted over a predetermined time span, or until the process realisation of all supplied elements reaches its conclusion. Simulation can also be realised either with or without an animation. The user can speed up the simulation by deactivating the animation and then activate the animation back. After completed simulation, we can view the generated final report (figure 53).



test dla rysunku.MOD (Normal Run - Rep. 1)

Name	Scheduled Time (HR)	Capacity	Total Entries	Avg Time Per Entry (MIN)	Avg Contents	Maximum Contents	Current Contents	% Utilization
Input Warehouse	113,610	5,000	75,000	20,134	0,222	5,000	0,000	4,430
Saw	113,610	1,000	75,000	11,375	0,125	1,000	0,000	12,516
Lathe	113,610	1,000	75,000	13,862	0,153	1,000	0,000	15,252
Milling Center	113,610	1,000	75,000	15,536	0,171	1,000	0,000	17,094
Inspect	113,610	1,000	75,000	2,649	0,029	1,000	0,000	2,915
Output Warehouse	113,610	1,000	75,000	0,000	0,000	1,000	0,000	0,000

Fig. 53. Final report in the standard version

During simulation resources' status is being displayed, or the current value of another logic element. The user – thanks to the option of displaying the current status – can trace every action in the entire model, or in a chosen part of it. The user can also observe during the simulation, what is happening at a given station, whether it is being occupied, redundant, or deactivated, by switching on the "status lights", changing colour depending on the current status. Statistical information can be presented graphically over the course of simulation, and exported to a spreadsheet either. The graphical form of charts can be in form of a 2D or 3D chart.

Amongst simulation options (Simulation menu/Options) are available options: length of performed simulation, system clock precision, types of generated final reports. It is also possible to switch on/off graphics displayed during simulation, cost calculation, pause upon the simulation start. The speed of graphics animation can be adjusted according to personal preference with the slider in the top part of screen.

Final report includes extensive statistics regarding all components of the modelled system.

5.3. Simulation results digest

Presented here report can slightly differ depending on the ProModel version used, it can also include additional statistics e.g. if in a model we define setup times for individual devices, we will get an information about how many setups were performed.

LOCATIONS

Location Name	Scheduled Hours	Capacity	Total Entries	Average Minutes Per Input	Average Content

Maximum Contents	Current Contents	% Utilization

LOCATION STATES BY PERCENTAGE (Multiple Capacity)

Location Name	Scheduled Hours	% Empty	% Partially Occupied	% Full	% Down

RESOURCES

Resource Name	Units	Scheduled Hours	Number of Times Used	Average Minutes Per Usage

Average Minutes Travel To Use	Average Minutes Travel To Park	% Blocked In Travel	% Utilisation

RESOURCE STATES BY PERCENTAGE

Resource Name	Scheduled Hours	% In Use	% Travel To Use	% Travel To Park	% Idle	% Down

FAILED ARRIVALS

Entity Name	Location Name	Total Failed

ENTITY ACTIVITY

Entity Name	Total Exits	Current Quantity In System	Average Minutes In System	Average Minutes In Move Logic	Average Minutes Wait For Res, etc.	Average Minutes In Operation

ENTITY STATES BY PERCENTAGE

Entity Name	% In Move Logic	% Wait For Res, etc.	% In Operation	% Blocked

From the level of report with statistics menu we have access to graphical results representation, which in a transparent manner shows accumulated information on manufacturing system elements.

A detailed final statistics analysis allows for understanding the operating principles of the constructed simulation model, and the behaviour of all elements of the examined manufacturing system.

The subsequent part contains exercises for didactical classes “Simulation of manufacturing processes” for the ZIP major at the Faculty of Mechanical Engineering of Wrocław University of Technology.

5.4. Teaching plan „Simulation of manufacturing processes”

EXERCISE 1 – deterministic model – determination of delivery frequency

EXERCISE 2 – quenching operation inclusion

EXERCISE 3 – QC operation inclusion

EXERCISE 4 – introduction of a diverse production plan

EXERCISE 5 – introduction of an assembly operation

EXERCISE 6 – definition of diverse means of transport and cost inclusion

EXERCISE 7 – non-deterministic simulation model of a production line

EXERCISE 8 – definition of work breaks and the use of macros

EXERCISE 9 – definition of variables and attributes, characterising analysed manufacturing system

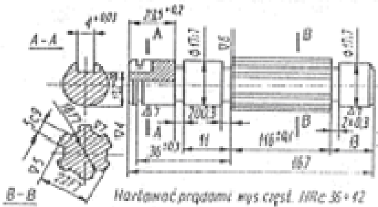
EXERCISE 10 – SimRunner program, first optimisation

EXERCISE 11 – SimRunner program, second optimisation

EXERCISE 1 – determination of delivery frequency

Make a deterministic simulation model of a manufacturing system according to the technological process presented below for the shaft nr 1 (Table 1).

Table 1. Manufacturing process scheme for element shaft nr 1 [57]

<table>
<tr><td colspan="2">Part No.</td><td colspan="7" rowspan="6">
</td></tr>
<tr><td colspan="2">1</td></tr>
<tr><td colspan="2">Part Name:</td></tr>
<tr><td colspan="2">shaft</td></tr>
<tr><td colspan="2">Material:</td></tr>
<tr><td colspan="2">40H</td></tr>
<tr><td>Number of operations:</td><td>**10**</td><td>**20**</td><td>**30**</td><td>**40**</td><td>**50**</td><td>**60**</td><td>**70**</td><td>**80**</td></tr>
<tr><td>Work-station:</td><td>Saw</td><td>Lathe</td><td>Keyway cutter</td><td>Horizontal Milling M.</td><td>Hardening</td><td>Cylindrical Grinder</td><td>Spline Grinder</td><td>Lathe</td></tr>
<tr><td>T_j</td><td>0,015</td><td>0,250</td><td>0,083</td><td>0,470</td><td>-</td><td>0,176</td><td>0,370</td><td>0,015</td></tr>
<tr><td>T_{pz}</td><td>0,15</td><td>0,52</td><td>0,30</td><td>0,50</td><td>-</td><td>0,32</td><td>0,40</td><td>0,15</td></tr>
</table>

Recommendations for modelling:

1. Locations – according to the enclosed figure, additionally IN and OUT storages (Capacity 5, FIFO)
2. Elements – the bar AT the enclosed figure (choose your own graphics)
3. Path – maintain the distance between neighbouring locations of 1.6 metres, L or U shaped production line.
4. Resources – 1 blue collar worker performs all technological operations and transport activities.
5. Technological process – AT the enclosed figure. Use command wizard in the module: Processing/Process and Process/Routing AT the scheme:
6. USE resource name FOR time value i.e. (for technological operations using resources),
7. MOVE WITH resource name THEN FREE – (for transport activities).
8. Production plan: produce 100 shaft items, delivery batch size of 5 units, time between the first delivery to simulation start – 0, compute number of deliveries, at the first simulation launch assume a time between deliveries.
9. Run simulation, analyse results, find optimum time between deliveries based on simulation results analysis.

NOTE:

- Correction of previously saved records in the simulation made is possible from the menu: Edit/Delete/Insert/Move/Copy Record/Paste Record, after prior pointer positioning next to the name of a resource being corrected.
- Manufacturing system model holds a special case – capacity of the storage resembles the size of a delivery batch – what induces deliveries in a particular time and doesn't allow for stock building up, there is no possibility of using safety stock
- Technological operations nr 20 and 80 are performed at the same lathe.

ECERCISE 2 – quenching operation inclusion

Please update the previous simulation model with next elements.

1. An additional worker, establish a new division of technological and transport operations,
2. Add quenching operation as the 50 operation (add location: hardening shop $T_j=2$, $T_{pz}=0.5$, order WAIT time value i.e. (for technological operations not using resources). Additionally required are going to be locations Pallet Before quenching, capacity 5, FIFO and Pallet after Quenching, capacity 5, FIFO), amend path for workers, use orders GROUP and UNGROUP AT the scheme in table 1:

Table 1. Scheme of describing quenching process using commands: group/ungroup

Process			Routing			
Item	Station	Operation	Output	Next station	Sorting rules	Transport activity
Item X	Stan. A	group *number of elements*	Item Y	Quenching shop	First 1	move with *resource name* then free
Item Y	Quenching shop	Wait t_j *time*	Item Y	Stan. C	First 1	move with *resource name* then free
Item Y	Stan. C	ungroup				
Item X	Stan. C		Process continuation …			

EXERCISE 3 – QC operation inclusion

Please update the previous simulation model with next elements.

Add quality control operation as the 90 operation (add location QC, where T_j=0.1, T_{pz}=0.25, uniformly 10% of components reach control).

Add in the module Processing/Process an instruction, used for choosing alternative paths: route 1 (element to control) and route 2 (element to OUT pallet).

Prior a counter needs to be defined – define it in the module Build/Variables (global), parameters: Integer, initial value 0 and route 2 in the Process/Routing window leading from the lathe operation 80 to quality control location.

Instruction for choosing transport paths:

```
counter = counter + 1
IF counter > = 10 THEN
    BEGIN
            route 1         comment: define route 1 as to control
            counter = 0
    END
ELSE
    BEGIN
            route 2         comment: define route 2 as to OUT storage
    END
```

Run simulation, analyse results, find optimum time between deliveries based on simulation results analysis.

NOTE:

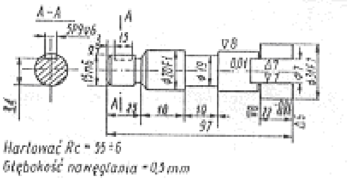
In the Processing module there is an alternative way of defining technological operations: after clicking in the Process and Routing window the bar Entity, Location, Operation and Output, Destination, Rule, Move Logic windows are available, in which there is a possibility of manual correction of chosen parameters.

EXERCISE 4 – introduction of a diverse production plan

Update the previous simulation model with:

1. Technological process for shaft nr 3 shown in the Table 1.

Table 1. Manufacturing process scheme for element shaft nr 3 [57]

<table>
<tr><td colspan="2">Part No.</td><td colspan="7" rowspan="6">
</td></tr>
<tr><td colspan="2">3</td></tr>
<tr><td colspan="2">Part Name:</td></tr>
<tr><td colspan="2">shaft</td></tr>
<tr><td colspan="2">Material:</td></tr>
<tr><td colspan="2">40H</td></tr>
<tr><td>Number of operations:</td><td>10</td><td>20</td><td>30</td><td>40</td><td>50</td><td>60</td><td>70</td><td>80</td></tr>
<tr><td>Work-station:</td><td>Saw</td><td>Lathe</td><td>Horizontal Milling M.</td><td>Lathe</td><td>Keyway cutter</td><td>Hardening</td><td>Cylindrical Grinder</td><td>Surface grinder</td></tr>
<tr><td>T_j</td><td>0,015</td><td>0,216</td><td>0,058</td><td>0,012</td><td>0,063</td><td>-</td><td>0,370</td><td>0,015</td></tr>
<tr><td>T_{pz}</td><td>0,15</td><td>0,47</td><td>0,30</td><td>0,47</td><td>0,37</td><td>-</td><td>0,40</td><td>0,15</td></tr>
</table>

Use the possessed machinery, add missing locations, divide again technological operations and transport activities between 2 workers, quenching and QC operations model AT assumptions from the exercise 2.

Lay out the production plan, so that the shaft 2 could be made in the quantity of 300, delivery batch size of 15 units, compute number of deliveries, for the first simulation assume a time between deliveries. Production plan should be as follows:

Table 1. Production plan

Product	Shaft nr 1	Shaft nr 3	Shaft nr 2	Shaft nr 3
Number of units	50	120	50	180

Production of the shaft 2 should commence possibly immediately after IN pallet is released, that moment should be found by means of a chart of elements content at the IN pallet after a curried out simulation, icon 📈 in the results module (choose IN Pallet Contents, in options you can choose time units on axes). Run simulation, analyse results, find optimum time between deliveries based on simulation results analysis.

NOTE:

- For shaft nr 3 technological operations nr 20 and 40 are taking place at a single lathe, hence it is necessary to define an inter-operational buffer, used before nr 40 operation. Otherwise the manufacturing process will become blocked.

- Remember about increasing the storage capacity up to the size of a delivery batch for shaft nr 3, although do not allow for stock build-up for shaft nr 1.

EXERCISE 5 – introduction of an assembly operation

Update the previous simulation model with an assembly operation.

Modelling assumptions:

1. Locations – add IN Pallet Assembly and an assembly station.
2. Assembled elements AT the scheme: type A bearing, 2 units for shaft 1 and type B and C one unit each for shaft 2.
3. Update the path, maintain distances between workstations of 1.6 m (in ProModel we enter decimal parts of the distance by using a dot).
4. Resources – no changes.

Technological process AT the enclosed example from previous exercises, include both T_j and T_{pz}. Use the join order under the scheme: JOIN number of elements element's name.

You should also amend the sorting rule for the bearing (module Processing/Routing window/Rule bar) with the IF JOIN REQUEST option with reference to the transport activity to the assembly station (table 1).

Table 1. Technological times for A, B, C bearings assembly

Element	Bearing A	Bearing B	Bearing C
T_j [h]	0.10	0.10	0.15
T_{pz} [h]	0.20	0.20	0.25

5. Production plan: adjust required bearings' quantity of all types.
6. Run simulation, analyse results, find optimum time between deliveries based on simulation results analysis.

EXERCISE 6 – definition of diverse means of transport and cost inclusion

Update the previous simulation model with a gantry crane for transporting grouped elements for quenching and a conveyor belt, transporting shaft 1 and 2 to the IN pallet. In order to do so you have to:

1. Add a route for the gantry crane – new transportation path of the CRANE type, defined by entering the end and beginning of both its guideways and nodes, at which the gantry crane is going to stop beside workstations. You should remember about interfaces between new nodes and workstations.
2. Define resources using the type CRANE route and the time of lifting an item of 30 s and lowering of 25 s.
3. Conveyor belt has the following parameters: capacity of 10 elements, transport speed of 7 km/h. Conveyor belt is defined as a workstation using the ▥ icon in the Location module, Graphics window. Double-clicking on the inserted object allows for editing its parameters.

Run simulation, analyse results, find optimum time between deliveries based on simulation results analysis.

Add counters describing the number of currently being produced elements – in the Variables (global) module clicking in the Location window will cause definition of a graphical form of the counter – you have to place an order of increasing the counter in the moment of transporting elements to the OUT pallet. Add a counter describing the in-progress production status – defined as the difference between number of elements which are currently issued into production and already made ones.

Use the cost module in order to determine the total cost of realising a production order. Determine the aggregate cost of realising the production process. The module is available from the Build/Cost menu, you have to propose costs of workstations' work, production resources per hour and cost of production materials.

EXERCISE 7 – non-deterministic simulation model of a production line

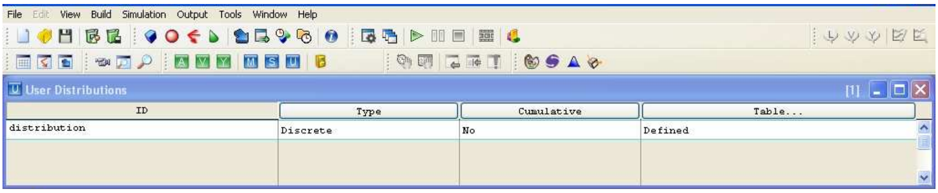
Make a new simulation model of a small manufacturing line producing stepped shafts and fitting them with bearings. Production process is realised in the following manner: from the IN storage elements are passed via a conveyor belt to an operator, who moves them to a chosen numeric machine tool NC_1 or NC_2. Amongst stations choose the one, which in a particular moment has got free capacity, which was predetermined in the Processing module, transportation activities window, the Rule column, by selecting command First 1 for NC_1 and First for NC_2. From numeric processing NC_1 or NC_2 elements are transferred to a deburring station, from where they go to control. If an element is flawless, it is fitted with a bearing, collected from the bearings buffer. In case of having detected a defect, the element is discarded (directed to the defective goods storage). Information about technological operations is included in the table 1:

Table 1. Manufacturing process scheme for stepped shaft element

Location name	Capacity	T_j [min]
IN storage	determine	–
Conveyor belt	determine	–
NC_1	1	2
NC_2	1	2
Deburring	1	5
QC	1	2,5
Bearings buffer	determine	–
Assembly	1	1,5
Defective goods storage	1	–
OUT storage	1	–

In the simulation model you have to define, using the standard graphical elements library, the following objects: workplaces (Locations), parts (shaft, bearing and waste), an employee operating all devices, route for the worker and elements, technological process AT enclosed table, production plans assume producing 12 units. Match the frequency of deliveries, to maximise the utilisation of production capacity. Additionally find the minimum stations capacity: IN Storage for shafts, bearing buffer and conveyor belt, in order for the production to operate smoothly, without any downtimes.

To determine, which elements are of an appropriate quality, use the probability distribution which you defined, from the menu Build/More Elements/User Distributions. In the Type field determine, that the distribution is discrete, and non-cumulative. The Table tab facilitates access to the table, where you can determine the probability expressed as a percentage and connected with its values for the distribution. If the distribution was to be continuous, the first entered value would have to be a percentage. Define the probability equal 70% with assigned value of 1, in case an element is of a good quality, and 30% with value of 0, in case of insufficient quality (figure 1).



ID	Type	Cumulative	Table...
distribution	Discrete	No	Defined

Fig. 1. Definition of own probability distribution

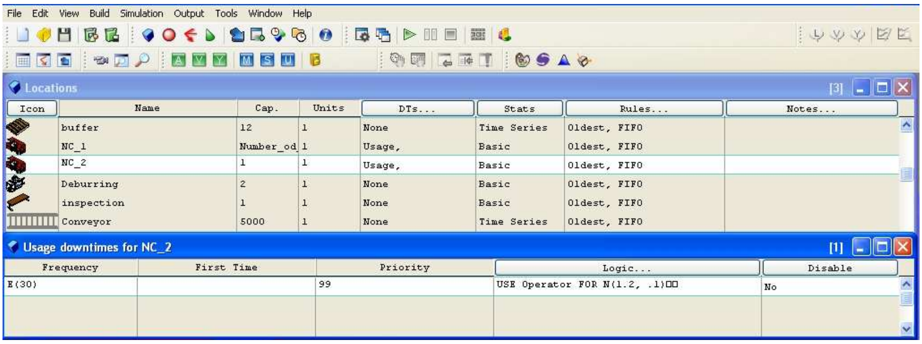
In the simulation model use the order if ... then ... else to separate good elements from defective ones. In case of good elements, they should be directed to assembly; in case of faulty elements they should go to the Defective Goods Storage, having changed their name simultaneously to waste. In the Processing module the Operation field for an element on the QC station, declare a local variable “Test” (by entering “INT test”) and assign to that variable distribution value “Test = Distribution()”, then use it in the order IF ... THEN ... ELSE. Expressions present a condition, influencing the further routing of the stepped shaft. Because if Test is equal 1, what means, that the stepped shaft had been made correctly, a subsequent command together with the bearing (Assembly station, order JOIN number of elements element). Then the operator is going to be need (the USE order) for N(1.5, 0.2), where N means normal distribution with expected value of time per unit of T_j=1.5 and variance of 0.2. If however Test equals naught, the second routing will be chosen (directing the element to the Defective Goods Storage).

EXERCISE 8 – definition of work breaks and the use of macros

Please update the previous simulation model with next elements.

1. **Work breaks of NC_1 and NC_2 machine tools**

Pauses occur every 1 hour and are described by the normal distribution N(1.2, 0.1), that time is necessary for the worker to perform an inspection upon devices. To define breaks use the Usage option in the Locations module (figure 1).



Icon	Name	Cap.	Units	DTs...	Stats	Rules...	Notes...
	buffer	12	1	None	Time Series	Oldest, FIFO	
	NC_1	Number_od	1	Usage,	Basic	Oldest, FIFO	
	NC_2	1	1	Usage,	Basic	Oldest, FIFO	
	Deburring	2	1	None	Basic	Oldest, FIFO	
	inspection	1	1	None	Basic	Oldest, FIFO	
	Conveyor	5000	1	None	Time Series	Oldest, FIFO	

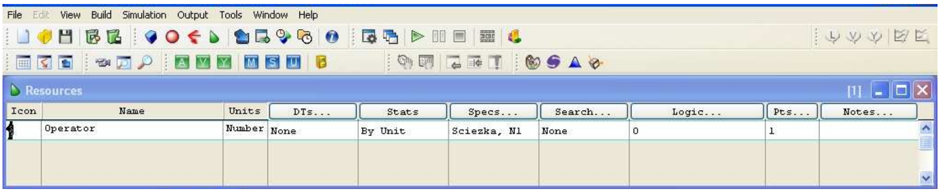
Frequency	First Time	Priority	Logic...	Disable
E(30)		99	USE Operator FOR N(1.2, .1)□□	No

Fig. 1. Definition of breaks for NC 1 and NC 2 machine tools

Applied Usage command defines the setup time by assigning a frequency, priority, whose value 99 means, that a given setup (in this case Usage) has got the precedence over other events of lower priority and a logic expression, where we define tasks during setup. The time is given as a normal distribution N(1.2, 0.1).

2. **Define the number of workers by means of a macro**

We define the number of workers by entering in the Units field the macro's name Number_of_Workers (figure 2). This expression has to be pre-established earlier in the Macros module (discussed below), at next tutorials this macro is going to be used as a variable in optimisation in the SimRunner program.



Icon	Name	Units	DTs...	Stats	Specs...	Search...	Logic...	Pts...	Notes...
	Operator	Number	None	By Unit	Sciezka, N1	None	0	1	

Fig. 2. Use of a macro for defining number of workers

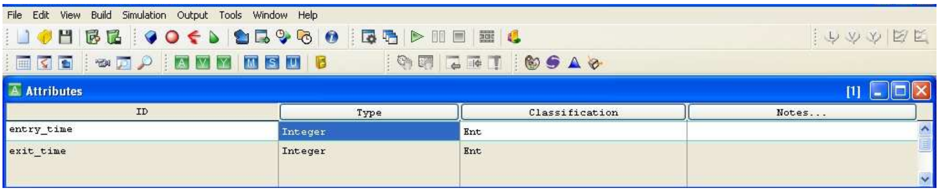
The Macros module contains the ID field for typing in a name for the macro and the Text field for entering an announcement or numerical expression, which is going to be the default value. Macro's default value is going to be used during conducting simulation without using the SimRunner. It is absolutely vital to determine the range of acceptable values of a macro (Options/RTI/define). Define then the following macro: "Number_of_Workers", value from 1 to 5, default of 1.

3. **Define the deburring station's capacity by means of a macro.**

In the Locations module use macro "Deburring_capacity", value from 1 to 7, default 1 to define that device's capacity. Change times of technological operations at stations NC_1 and NC_2 to T_j=N(3,0.2), deburring -> T_j=N(1.5,0.2), KJ -> T_j=N(3.2, 0.3), carry out several simulative examinations, review statistics for differences resulting from application of random variables. Run the simulation e.g. 5 times (Simulation/Options/Number of Replications).

EXERCISE 9 – definition of variables and attributes, characterising analysed manufacturing system

Include in the simulation model various kinds of variables, to create a description of parameters of the manufacturing process being realised. By means of attributes, you have to find the cycle time for elements in the production process – figure 1.



ID	Type	Classification	Notes...
entry_time	Integer	Ent	
exit_time	Integer	Ent	

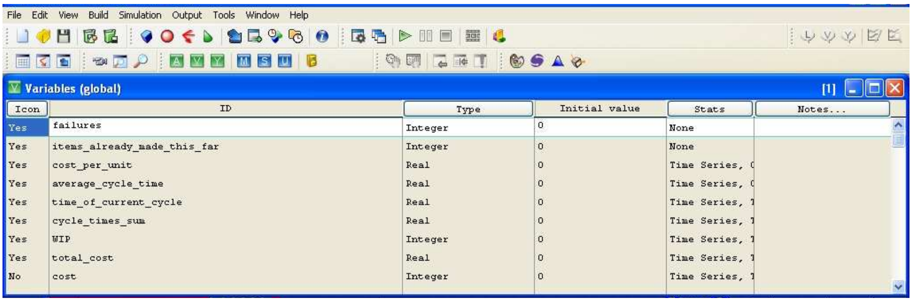
Fig. 1. Attributes definition

Attributes are defined in an appropriate module, two attributes are going to be needed:

- ➢ entry_time,
- ➢ exit_time,

Numeric expressions of individual attributes can be described by either real or integer numbers. Attribute in the Classification tab can be assigned to a station or an item. In this module define variables describing functioning of the modelled manufacturing system.

Required counters (figure 2):



Icon	ID	Type	Initial value	Stats	Notes...
Yes	failures	Integer	0	None	
Yes	items_already_made_this_far	Integer	0	None	
Yes	cost_per_unit	Real	0	Time Series,	
Yes	average_cycle_time	Real	0	Time Series,	
Yes	time_of_current_cycle	Real	0	Time Series,	
Yes	cycle_times_sum	Real	0	Time Series,	
Yes	WIP	Integer	0	Time Series,	
Yes	total_cost	Real	0	Time Series,	
No	cost	Integer	0	Time Series,	

Fig. 2. Definition of global variables

- ➢ failures (elements discarded after quality control),
- ➢ items already made this far,
- ➢ cost per unit,
- ➢ average cycle time,
- ➢ time of current cycle,
- ➢ cycle times' sum,

- WIP (items in the process i.e. ”Production in Progress”),
- total cost.

Those counters should have their graphic representations (menu Background Graphics/Behind Grid, please use the icon bar on the left side of the screen, double-clicking on the already inserted object will call out its properties – figure 3).

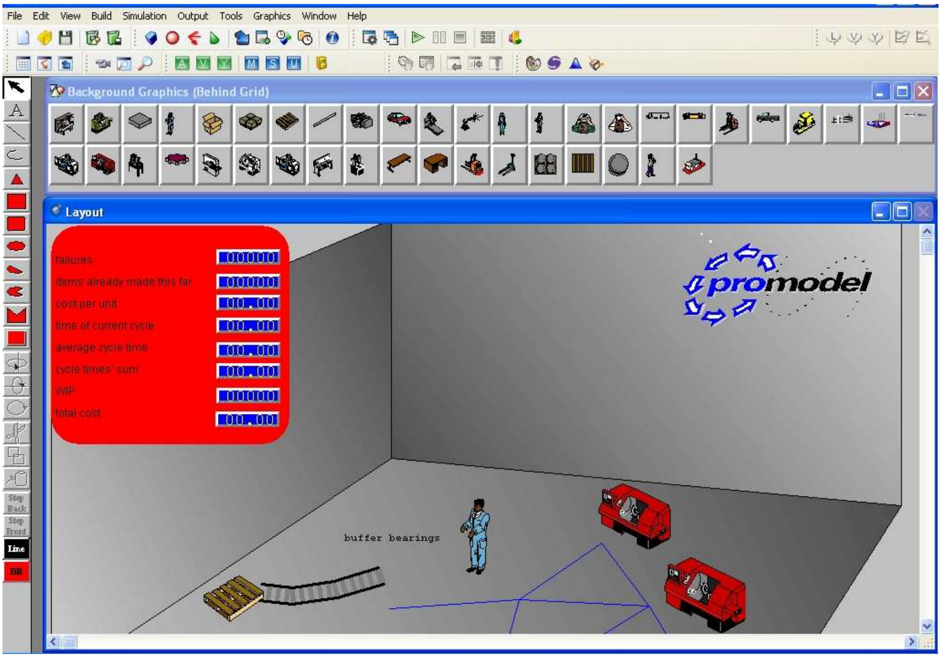


Fig. 3. Definition of counters’ graphical form on a graphical underlay

Prompt: upon element’s exit from the system you have to:

- increase the overall number of all produced items thus far, e.g. order INC variable, value,
- calculate cost per item (total cost divided by the number of all manufactured items)
- calculate current cycle time – in the moment, when the stepped shaft is supplied to the conveyor belt, please start the clock with the function Clock (time unit), showing the entry time of an element into the system. The form of the order can be defined in the following manner: Entry_time = Clock(Min), the value of occurrence time of that event will be stored in the attribute, which distinguishes times for each element separately. Then, when the stepped shaft is delivered to the storage we reiterate the

measurement of the time Exit_time = Clock(min), also using the attribute. The difference of those two attributes will show us, how long an element has spent within the production system. For a next element, which will reach the OUT storage, measurement and finding of the current cycle time is repeated.

- increase the value of the sum of cycle times of items staying within the manufacturing system by the time of current cycle (e.g. INC sum of cycle times, current cycle time
- calculate the average cycle time (sum of cycle times of items staying within the manufacturing system divided by the complete number of those items),
- decrease the number of items in the process, e.g. order DEC variable, value. For elements qualified as wastes you have to:
- increase the number of discarded items,
- decrease the number of items staying within the process.

After the assembly operation assign to the variable total_cost the value of costs ("INC total_cost, GetCost()" – function GetCost() returns the current value of an element, using statistics conducted during the model's simulation). Earlier you need to assign exemplary costs to elements, resources and locations (Build/Cost), and uncheck the option Disable Cost (Simulation/Options).

EXERCISE 10 – SimRunner program, optimisation step by step

SimRunner uses the existent simulation model created in the ProModel – based on the data extracted from the model it proposes the best possible solutions [61]. Data analysis and optimisation is performed automatically. For an every simulation project the designer decides, which model to analyse or optimise, which input factors should be altered and how to measure outcomes of the simulation system. In the SimRunner module one can conduct two types of projects:

1. Optimisation model: multi-criteria optimisation, which tests various combinations of input factors, in order to obtain the best value of the objective function.
2. "Analysing model": helps to find the number of system replications requisite for estimation of an average objective function value taking into account the margin of error and confidence level and support in finding time of running for the model, which will help to achieve a stable behaviour of the objective function.

SimRunner generates three types of data and reports [41]:

1. Data, reports entered into a spreadsheet.
2. Text and report analysis from the optimisation process.
3. Diagrams graphically representing obtained results.

Code of practice for optimising a simulation model, presents as follows [70]:

1. Creation, verification and approval. The most important stage in preparing a model for optimisation is its validation, only after model's approval, optimisation can commence.
2. Project construction. Based on the simulation model, which will be optimised, a new project is created in the SimRunner. First we define the form of results, which we would like to obtain, then determine the objective function, evaluation system of introduced improvements. Subsequently we select input factors, which are optimised by the SimRunner in order to obtain the best possible system refinement.
3. Experiment conducting. After choosing input factors and determining the objective function, we can use the SimRunner to automatically conduct a series of experiments on the simulation

model. The SimRunner carries out the simulation and tests different possible combinations of values and factors. Then the SimRunner completes the test and presents obtained simulation experiment results in a particular order, from the most successful to the least auspicious combinations of values of considered factors.

4. Suggestion estimation. The forth step is consideration and estimation of suggestions made by the program. This choice is crucial, because SimRunner often generates several solutions of a ruminated problem, and a decision about chosen optimum values can include factors unrelated to the simulation model. Examples of such factors could be: restriction related to the economic situation of a company. One can additionally run an extra simulation to narrow down confidence intervals, to facilitate the evaluation of consecutive, possible solutions generated by the SimRunner.
5. Obtained results implementation. A well recognised problem and solidly conducted optimisation is the basis for implementing obtained results.

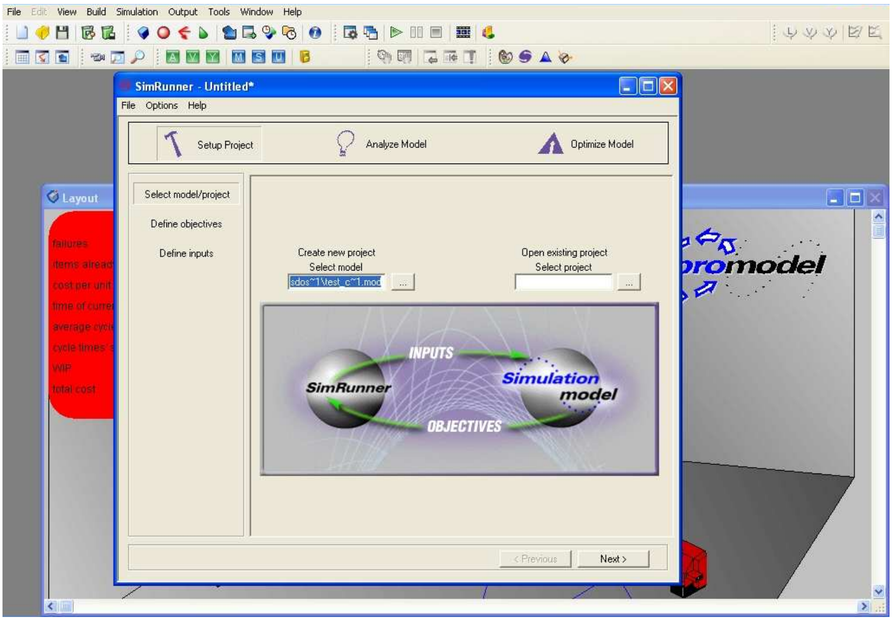
Conducting an optimisation of a simulation model

Before starting works in the SimRunner module, please set the technological operation time of deburring to $T_j = 2$ min.

A project in the SimRunner module is built based on an existing simulation model. Please select the manufacturing system model, which is going to be subject to the optimisation (from the previous exercise), then launch the SimRunner module (Simulation\ SimRunner) save the ProModel file and click the Next button (in this way we assume a new optimisation project – figure 1).

Definition of optimisation criteria

Please select the following optimisation criteria (choose from the Response category, then more detailed criteria from the Response statistic, selection buttons are situated below the window, chosen criteria will appear in the Response statistics selected for objective function window).



Select model
sdos~1\test_c~1.mod

Fig. 1. Selection of a model for optimisation

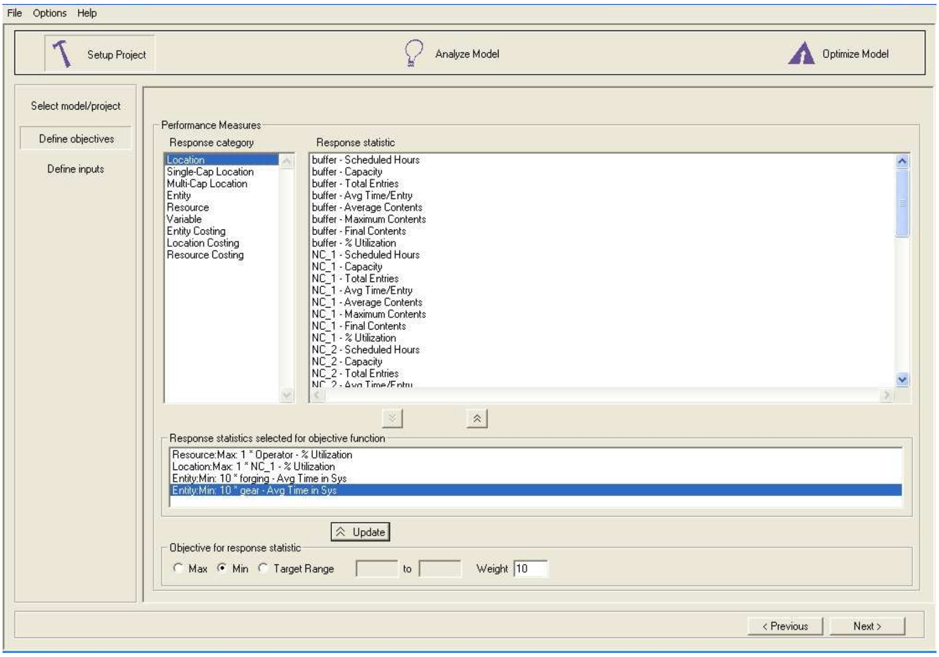
The Objective for response statistic panel, allows for giving weights to criteria and determining, whether we put greater stress on their minimisation or maximisation. Values are entered by the Update button. Values to enter (figure 2):

- maximum utilisation of workers, weight 1 (Resource\Worker, % Utilization)
- maximum load of machine tools NC_1, weight 1 (Location\ NC_1, % Utilization)
- minimum average time of an element in the system, weight 1 (Entity\bar\Avg time in Sys).

Criteria in SimRunner are constituents of the objective function, which is calculated from the following algorithm:

O. Function = MAX(weight)*criterion1 + MAX(weight)*criterion2 + MIN(weight)* criterion 3 + ...

Values of criteria can differ by even several orders of magnitude, therefore weights assigned to criteria are used, in order to balance out their influence on the objective function. To progress to the next screen we select the Next button.



Performance Measures

Response category
Location
Single-Cap Location
Multi-Cap Location
Entity
Resource
Variable
Entity Costing
Location Costing
Resource Costing

Response statistic
buffer - Scheduled Hours
buffer - Capacity
buffer - Total Entries
buffer - Avg Time/Entry
buffer - Average Contents
buffer - Maximum Contents
buffer - Final Contents
buffer - % Utilization
NC_1 - Scheduled Hours
NC_1 - Capacity
NC_1 - Total Entries
NC_1 - Avg Time/Entry
NC_1 - Average Contents
NC_1 - Maximum Contents
NC_1 - Final Contents
NC_1 - % Utilization
NC_2 - Scheduled Hours
NC_2 - Capacity
NC_2 - Total Entries
NC_2 - Avg Time/Entry

Response statistics selected for objective function
Resource:Max: 1 * Operator - % Utilization
Location:Max: 1 * NC_1 - % Utilization
Entity:Min: 10 * forging - Avg Time in Sys
Entity:Min: 10 * gear - Avg Time in Sys

Objective for response statistic
○ Max ● Min ○ Target Range ☐ to ☐ Weight 10

Fig. 2. Criteria defining

Choosing parameters for optimisation

The system parameter chosen for optimisation is the number of worker and the capacity of tooling machine NC_1 (this is roughly equivalent to their quantity). The number of workers was defined earlier in the model by means of a macro, macro's values corresponds to the number of workers. Macros characterise three parameters:

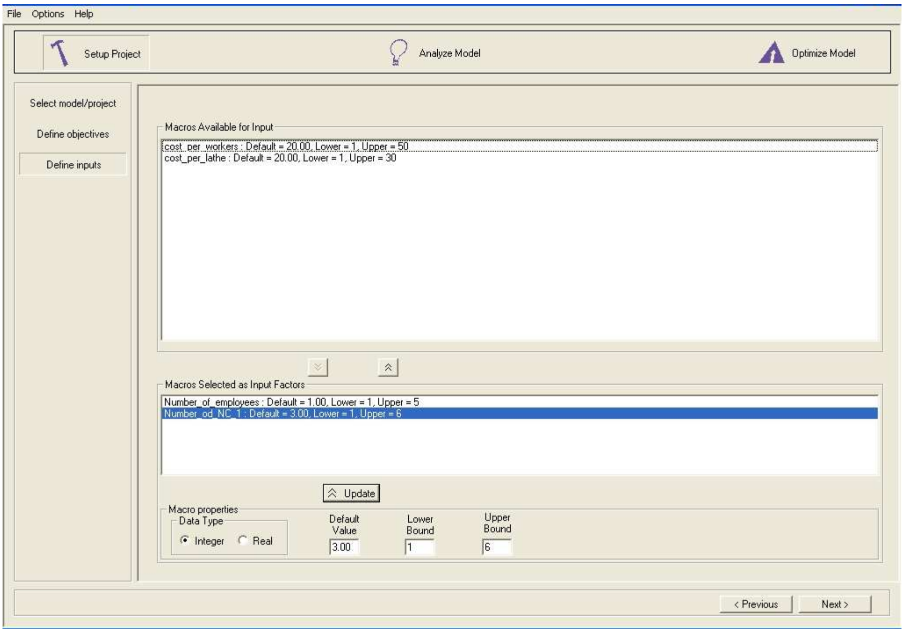
1. initial value: 1 worker,
2. maximum value: 5 workers,
3. minimum value: 1 worker.

Please also introduce a macro for describing the capacity of machine tool NC_1 (values from 1 to 6, default 3), save the file in ProModel and SimRunner.

SimRunner conducts simulations using every value of a macro, as well as will consider every possible combination of those values. Macros defined in the model are presented in the Macros Available for Input window (figure 3), by clicking buttons we select ones of our interest (not all need to be used), we can also influence their values taken into account during the optimisation (the Macro Properties panel, Update button).

NOTE:

Please remember, to make changes to the model subjected to optimisation – consisting of adding additional macros – with the SimRunner program off, otherwise improvements would not be visible in the optimised model.



Macros Available for Input

cost_per_workers : Default = 20.00, Lower = 1, Upper = 50
cost_per_lathe : Default = 20.00, Lower = 1, Upper = 30

Macros Selected as Input Factors

Number_of_employees : Default = 1.00, Lower = 1, Upper = 5
Number_od_NC_1 : Default = 3.00, Lower = 1, Upper = 6

Macro properties

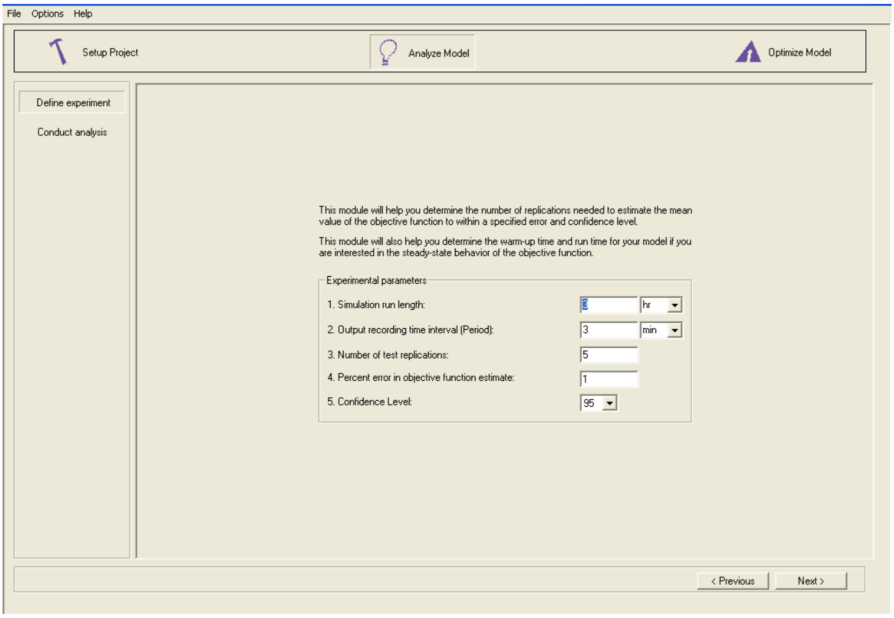
Data Type: ● Integer ○ Real

Default Value: 3.00
Lower Bound: 1
Upper Bound: 6

Fig. 3. Selection of parameters for optimisation

Analysing Model

An analysing model helps to find number of system replications required for estimation of an average value of an objective function minding margins of error and confidence levels and a support in finding the running time of a simulation for a model, which will help in understanding stable behaviour of the objective function. The central issue is conducting every simulation under identical boundary conditions, only then there is sense in comparing obtained simulation results. If all aspects of an analysed system model are deterministic (there are no random variables in any part of the model), the number of experiment replications can equal 1. Otherwise one needs to assume the number of test replications e.g. 5 and check how many replications will be suggested in order to achieve an assumed confidence level. Please enter the above values AT the figure 4, click Next, then we reach the screen from figure 5, click the Run button and we get a graph of objective function values differences for deterministic and stochastic data.



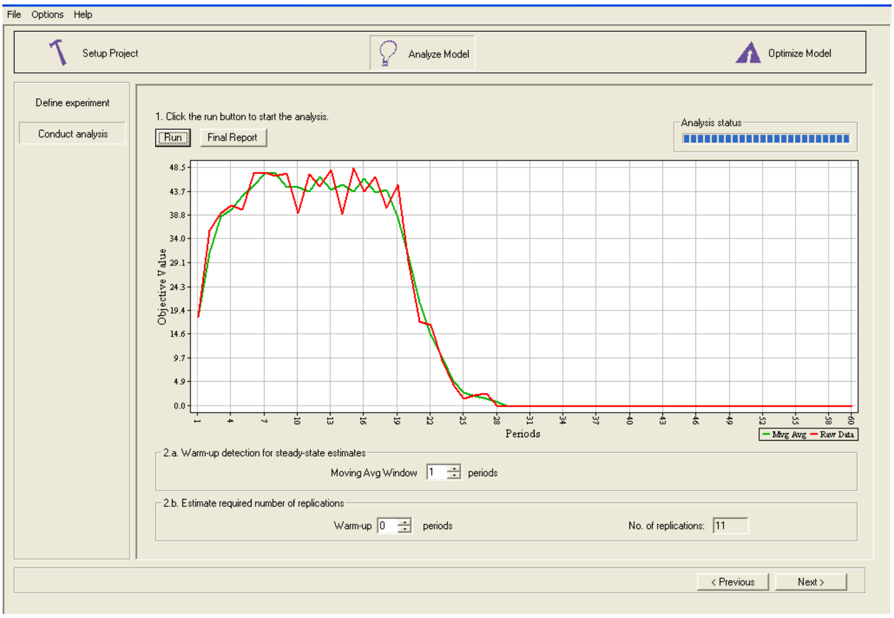
This module will help you determine the number of replications needed to estimate the mean value of the objective function to within a specified error and confidence level.

This module will also help you determine the warm-up time and run time for your model if you are interested in the steady-state behavior of the objective function.

Experimental parameters

1. Simulation run length: 3 hr
2. Output recording time interval (Period): 3 min
3. Number of test replications: 5
4. Percent error in objective function estimate: 1
5. Confidence Level: 95

Fig. 4. „Analysing” model parameters



1. Click the run button to start the analysis.

2.a. Warm-up detection for steady-state estimates

Moving Avg Window 1 periods

2.b. Estimate required number of replications

Warm-up 0 periods

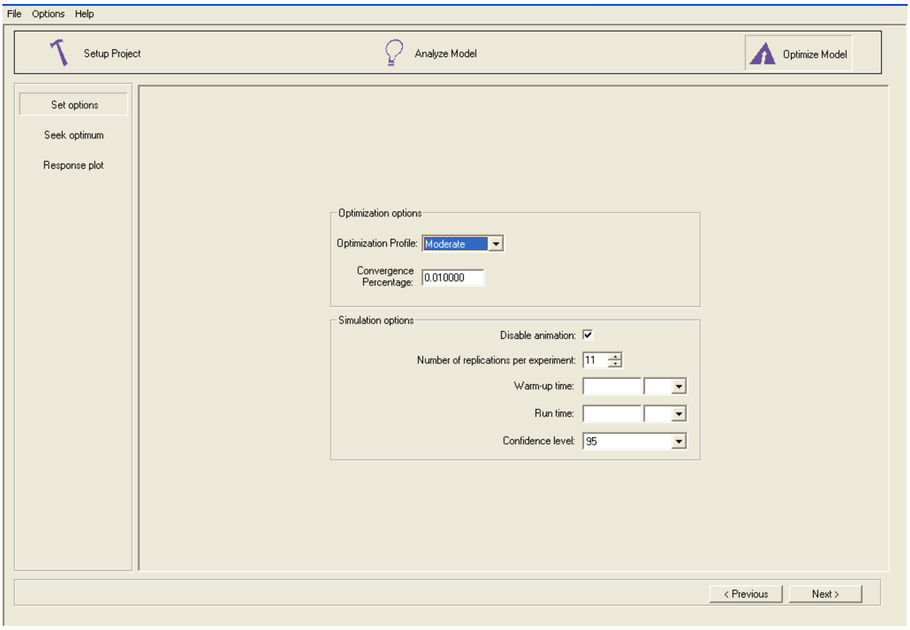
No. of replications: 11

Fig. 5. Results of „analysing” model

We also have the ability to enter information about the “warm-up” of the manufacturing system, please leave that data default. For the next step though, we read the suggested number of test replications – in this case the number is 11.

Definition of optimisation and simulation parameters.

Optimisation parameters: optimisation profile (moderate) and convergence percentage. Simulation parameters: deactivate animation, to shorten the time of running experiments. Please determine the entered earlier number of test replications for the experiment. System warm-up time was undefined (the time at the beginning of each experiment, after which SimRunner starts to gather data from simulation), because it is very small in comparison with the time of the entire simulation and is insignificant for obtained results. Duration of the experiment wasn’t defined either, what causes, that the simulation of each experiment will conclude only after producing the assumed size of the production batch. The confidence level determines the interval of average value of objective function, when the number of experiment replications is greater than one – figure 6.



Optimization options

Optimization Profile: Moderate

Convergence Percentage: 0.010000

Simulation options

Disable animation: ☑

Number of replications per experiment: 11

Warm-up time:

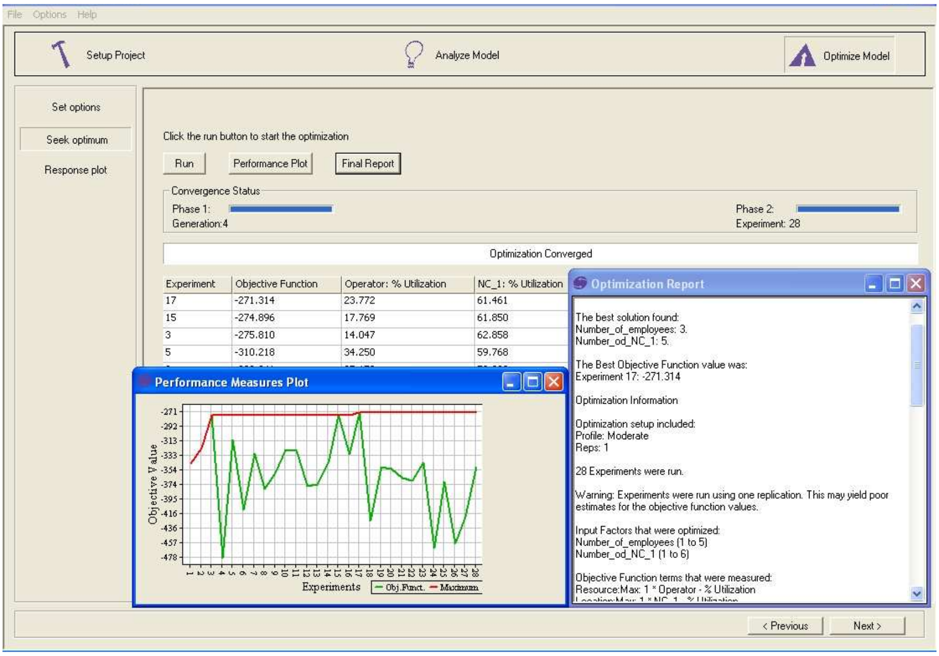
Run time:

Confidence level: 95

Fig. 6. Definition of optimisation and simulation parameters

Running experiments, simulation results

SimRunner conducted 29 experiments, each one for a different number of workers and NC capacity, read out values of criteria and for each case estimated objective function value. An optimum solution proposed by the SimRunner is an experiment, for which objective function value has the highest value. The optimum suggested by the SimRunner program is the variant with 3 workers and 3 NC stations, achieved in the 20th experiment, objection function value of 325.5. The Final Report button will display a short summary of obtained results – figure 7.



Click the run button to start the optimization

Convergence Status

Phase 1:
Generation:4

Phase 2:
Experiment: 28

Optimization Converged

Experiment	Objective Function	Operator: % Utilization	NC_1: % Utilization
17	-271.314	23.772	61.461
15	-274.896	17.769	61.850
3	-275.810	14.047	62.858
5	-310.218	34.250	59.768

The best solution found:
Number_of_employees: 3.
Number_od_NC_1: 5.

The Best Objective Function value was:
Experiment 17: -271.314

Optimization Information

Optimization setup included:
Profile: Moderate
Reps: 1

28 Experiments were run.

Warning: Experiments were run using one replication. This may yield poor estimates for the objective function values.

Input Factors that were optimized:
Number_of_employees (1 to 5)
Number_od_NC_1 (1 to 6)

Objective Function terms that were measured:
Resource:Max: 1 * Operator - % Utilization

Fig. 7. Conducting experiments, simulation results

Achieved results can differ, depending on discrepancies in Your simulation models subjected to optimisation. By clicking the Next button, you can advance to the next screen, where you will get a graph showing changes in objective function values, by selecting appropriate values on axes.

Please run few experiments selecting different macros to optimise, criteria values, conduct model analysis, find number of replications and draw the objective function graph.

EXERCISE 11 – SimRunner program, advanced optimisation

Choose the simulation model from exercises 8 and 9 for analysis and optimisation, please save that file with a name e.g. opt_cw2_z1. Conduct optimisation for:

- number of workers,
- deburring capacity,
- delivery frequency.

Those values are represented in the model by macros. Define lacking macros in the simulation model – frequency of deliveries (match values appropriate for your model, e.g. min value of delivery frequency cannot render those deliveries unable to be completed). Then select optimisation criteria:

- max worker's load,
- min of variable "average_cycle_time" – an average value,
- min of variable "PIP" – an average value,
- min of variable "total cost" – an average value.

Conduct an optimisation for each of criteria individually, save its results (right-click on optimisation results and select "save grid data" – results can be saved to a text file). Draw an average value of the objective function (the "Objective Function" column) for each of criteria (to do so use a spreadsheet for example), compare those values in order to be able to obtain information on each criterion's influence. Then propose your own weights for each of criteria, e.g. assume, that the criterion of the highest average value will take the value of 1 (SimRunner doesn't accept weight lower than 1, weights have to be rounded to integers). Run an optimisation for the sum of all criteria, entering the designated weights. Average drawing operations for individual criteria of the objective function and weights designation do in an available spreadsheet, save the results of conducted optimisation to computer hard drive.

5.5. Logic orders used in ProModel

An important element, facilitating determination of process logic by a user are logic commands. Logic commands are determining certain actions or logic operations. Usually they are related to some events such as an element's entry to a given station [70].

Logic commands are divided into expressions:

1. basic,
2. operational,
3. related to an element leaving a station,
4. related to elements' arrival,
5. related to exclusion,
6. resource orders,
7. orders determining start and end,
8. orders regarding pauses and shifts.

Basic expressions (commands). Basic expressions can be used as elements of an any logic and include commands such as:

- Activate – start an independent subroutine, i.e. user-defined subprogram or a command group,
- Animate – stops or starts animation and sets its speed,
- Assignment – assigns value of a numeric expression to a variable, attribute or array of variables,
- Close – closes a file opened by commands: Write, Writeline, Read,
- Comment – user comments – are not taken into account during simulation,
- Dec – decreases value of a variable, element from the array of variables, or an attribute by a numeric expression,
- Display – brings a simulation to a halt and displays an optional message with a value,
- Inc – increases value of a variable, element from an array of variables or an attribute by a numeric expression,
- Log – comprises time stored in a variable, attribute or array of variables from current clock time and registers it, to make it visible in the output module,
- MapArr – assigns unique variable's values to each of array cells,
- Order – causes creation of a certain number of elements and their injection into the system to a designated station,

- Pause – causes the simulation to stop until user selects the Resume option from the Simulation menu, appearing over the course,
- Prompt statement – causes the simulation to pause and display a message and an input field or a selection menu. The entered or selected value is subsequently assigned to a designated variable, element from an array or an attribute.
- Read – causes the next number to read from the general read file and its assignment to a variable, element from an array or an attribute,
- Report – calculates and compiles a report from current statistics into an external database,
- Reset – in case of a written file, causes creation of a file or if it exists it is erased and opened for writing, in case of a read file, a file is opened and ready to be read from the beginning, used together with Report,
- Send – sends a request of importing a defined number of particular item's types to a designated station.
- Sound – activates sound defined in the sound file,
- Stop – causes a simulation to discontinue running and if message is compiled it will be displayed,
- Trace – activates or deactivates the trace and displays a certain message for the user by means of user logic.
- View – changes the view in the window to Layout plan of arranged objects by means of an user's logic,
- Warm-up – allows for the simulation to run until the system reaches its equilibrium (state of balance), statistics are accumulated only after the warm-up period ends,
- Write/Writeline – causes a numeric or text expression to be saved in the general read file,

  Basic commands also include **control orders**.
- Begin/End – defines start and end of an expression block, being a group of orders executed together,
- Break – used in loop inside a message block, causes a break out, exit from the loop and continuation of performing the next message inside the block,
- BreakBlk – causes exit from the current message block and continuation upon the next message outside the block,

- Goto – causes model to skip to a message determined by a designated label,
- If – then – causes message or message block execution only if, the Boolean expression is true.
- If – then – else – causes message or message block execution only if, the Boolean expression is true, otherwise another order or order block is realised,
- Return – ends subroutine realisation and optionally returns value of the notifier message, if it appears in other logic to subroutine like a tough break and completely exits the thread,
- Do While – repeats a message or message block in a continuous manner, when the condition remains true. Do – While is a loop, which is always executed at least once.
- While Do – causes repeatable execution of a message or message group as long as the condition is fulfilled, if a condition is not fulfilled the message is not executed even once.

Operational expressions (commands). Operational orders are commands followed by an item, upon its arrival at a station and contain orders related both to the item and a resource, including also basic commands.

Operational expressions associated with the item:

- Accum – delays the process upon an item until a certain number of items is accumulated, after accumulation of items the process is continued,
- Combine – combines item of one kind or different kinds into a single item,
- Create – creates a particular number of items from a current item, every new item retains attributes of the original item,
- Graphic – causes change of current item’s graphic to a predetermined number for the graphics index, which was defined for a given item,
- Group – combines certain number of items of a given kind into a single item, items constituting the groups are stored and re-activated with the Ungroup order,
- Join – joins a particular number of items of a specific kind with a current item. Items after being joined lose their identification.
- Load – load a specific number of items to a current item, items after being loaded retain their identification until the next unloading by the Unload message,

- Match – causes waiting until the value of certain attributes of items being in the process is matched with the value of equivalent attribute of another item in the system,
- Move – moves items to the end of a queue or a conveyor belt, Move with – moves an item using a designated resource, Move for – determines the time required to move an item,
- Rename as – determines a new name for a current item,
- Route – causes selection by an item a particular route block,
- Split as – splits an item into several items and assigns them new names, new items have got identical attributes with the original item,
- Ungroup – ungroups items grouped by the Group message,
- Unload – unloads items loaded with the Load message, causes that the item transporting other items – loaded with them by Load or Group messages – unloads a certain number of those items upon encountering a pre-established condition,
- Wait – delays an item's process until a predetermined time lapses,
- Wait Until – delays execution of a certain message block until a particular Boolean variable becomes fulfilled.

Operational commands associated with a resource:

- Free – frees up a resource acquired by an item,
- Get – assigns a resource or resource combination to a technological operation or transport activity AT optionally determined precedence,
- Jointly get – assigns a combination of resources AT optionally determined precedence for a task, when acquiring multiple resources none will be acquired, until all will be available. The difference between Get and Jointly get for several resources is, that the Get message causes acquisition of resources as soon as they become available, whereas Jointly get doesn't acquire any resources until all are available.
- Use for – uses a resource or combination of resources for a task, AT optionally determined precedence, if resources become available. It means utilisation of a resource for a certain time period, and then release of it when the time lapses.

Exit (from a station) commands are executed, when an item leaves a station and can contain general commands as well as graphic orders.

Orders arrive, are executed upon items entry to the system and can contain general orders and graphic orders.

Exclusion orders can be performed when exclusion occurs and can contain general messages apart from those, which refer to whichever attribute type. Additionally the following operational commands can be used: free, get, graphic, jointly get, use, wait.

Resource orders are executed, when a resource arrives at a network node or departs from it. They are defined in the node editor. They can contain general commands as well as graphic orders.

Start and end orders of a simulation are executed at the beginning and end of a simulation. They can contain general orders.

Change and break orders are orders during writing changes and logic of breaks, which control what is happening when resources and stations are not working.

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