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INDUSTRIAL PLANTS II

Chapter 3 ï part 4:

Numerical simulation - WITNESS

DOUBLE DEGREE MASTER IN

ñPRODUCTION ENGINEERING AND MANAGEMENTò

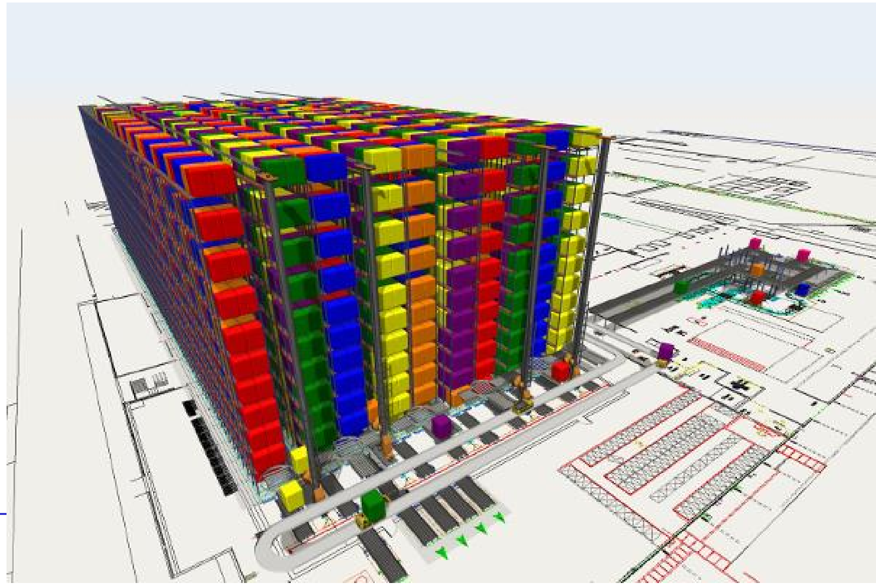
CAMPUS OF PORDENONE

UNIVERSITY OF TRIESTE

Numerical simulation as a tool for optimizing a production system

Simulation technologies

Due to the complexity of the problems faced in industrial plant engineering, proceeding analytically most of the time does not make it possible to obtain a solution to the problem. Here **simulation** represents a fundamental tool in all these cases, allowing a numerical approach. Precisely for this reason the simulation methods are now applied in the field of plant engineering in the search for the most disparate technical solutions, obtaining, in the majority of cases, extremely interesting results.



Numerical simulation as a tool for optimizing a production system

Simulation technologies

As an example we have:

a) **Simulation technologies to support decisions**:
   DSS (Decision Support System);

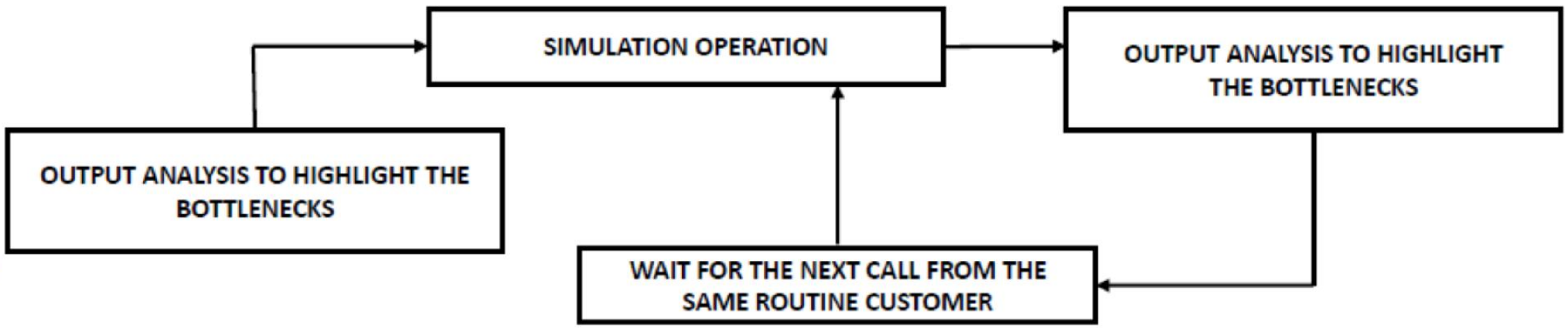
b) **Simulation technologies to support product design and engineering**:
   MBS Simulation (Multibody Modeling);
   BEM Simulation (Modeling of boundary elements);
   SEA Simulation (Statistical Energy Analysis);
   CFD Simulation (Numerical Fluid Dynamicx Analysis);
   FEM Simulation (Finite Element Method);

c) **Simulation technologies to support the analysis of processes of manufacturing and process industry**:
   CAM (Computer Aided Manufacturing);
   CAPP (Computer Aided Process Planning);
   Virtual Commissioning.

Numerical simulation as a tool for optimizing a production system

<u>Optimization by simulation</u>

Historically, the biggest **drawback of simulation** was that it was not an optimization technique. An analyst simulated a relatively small number of possible configurations of the system under consideration and selected the one that provided the best performance. Thanks to the development of computers and the improvement of optimization techniques, this disadvantage has been overcome, so that to date almost all simulation software have optimization functions. The **optimization process through simulation** (**SBO - Simulation-Based Optimization**) is an iterative process. Given the very high number of possible system configurations, the need for efficient algorithms to obtain the optimal solution in a reasonable time is evident (figure).



Numerical simulation as a tool for optimizing a production system

Simulation tools

After building the **logical-mathematical model**, it must be translated into a program. For this purpose it is possible to use different tools:

a) **ñgeneral purposeò languages**, such as C^{++}. They were widely used at the birth of the simulation, but require considerable effort in implementing the program. This is why we prefer to use other languages;

b) **specific simulation languages**, which provide predefined instructions for creating the logical-mathematical models, so as to reduce the time of realization of the program. Some examples are MODSIM, SIMSCRIPT etc .;

Numerical simulation as a tool for optimizing a production system

Simulation tools

After building the **logical-mathematical model**, it must be translated into a program. For this purpose it is possible to use different tools:

c) **interactive simulators**, which are application-oriented simulation packages. There are many, some examples are WITNESS®, ARENA®, EXTEND® etc.

Some are quite general even if they are dedicated to single types of systems such as industrial plants and communication systems, others are very specific such as, for example, nuclear power plant simulators or cardiovascular physiology simulators.

The simulators allow you to build a simulation program using graphical menus, without therefore the need to program.

However, they have the limitation of being not very versatile.

Simulation tools

After building the **logical-mathematical model**, it must be translated into a program. For this purpose it is possible to use different tools:

c) interactive simulators

Most of them limit themselves to modeling those systems foreseen by their standard characteristics.

To overcome this drawback, some of these simulators provide for the possibility of incorporating a code written in a general purpose language.

As an advantage, they often have the ability to show simulation in action through animation.

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS®

The **WITNESS® program**, developed by LANNER Group Ltd, is a discrete event simulation software used by thousands of companies around the world, as well as by most academic institutions. It is available in a version, called Manufacturing Performance Edition, entirely dedicated to production systems, which allows you to easily model even the most complex manufacturing systems, using the numerous predefined elements that are available.

This simulation software does more than just facilitate the modeling of a complex system and simulate its behavior, but provides statistical estimates of how it could develop over time. It also allows, once defined an objective function dependent on certain parameters, the search for the optimal configuration that maximizes it.

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS®

In other words, **WITNESS®** represents a simple and risk-free virtual laboratory in which to experiment and optimize the various decision-making choices.

In a "**hypercompetitive**" context such as today, where innovation is a key element in maintaining competitiveness on the market, software like this is an essential tool.

To test the potential of this software, an example of the configuration of a simple production line will be analyzed. After modeling the line and establishing a basic configuration, we will proceed with the simulation and the search for the optimal configuration.

In this work WITNESS® Horizon 20.00 Manufacturing Performance Edition was used, the version of the software entirely dedicated to production systems. A Service Edition version dedicated to services in general is also available on the market.

Simulation tools: WITNESS® - Ambiente di simulazione

A simulation environment is a combination of space and time in which work stations (machines), accumulation stations (buffers), conveyor rollers, etc. are located.

By activating a button the time starts to start: from this point the events follow one another in response to planned signals, inputs from input files or random events generated according to particular probability distributions. The simulation model uses two "zoom" functions:

- one for the **spatial dimension**;
- one for the **temporal dimension**.

In this way it is possible to speed up the simulation or to slow it down to analyze every single event in step-by-step mode.

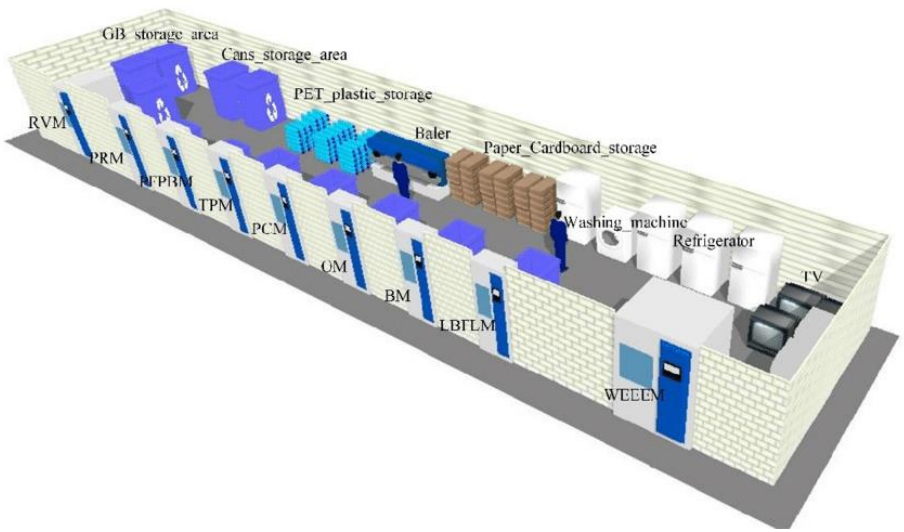
Simulation tools: WITNESS® - Ambiente di simulazione

In the workspace elements called parts move, **labors** and programmed transformations and random events occur.
The parts are characterized by **attributes**, which they carry with them on their journey along the model and which, interacting with the machines, determine the **succession of events**. The parts enter the environment with deterministic procedures or random events, they are transformed, modified and moved from one station to another, between machines and buffers. The sequence of events, the scan of operations, the number of accumulations, the time of events and all other situations associated with a numeric or textual variable can be stored in **variables**.

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Ambiente di simulazione

Data sets with predefined layout can be recorded in **files**, read by the model or written in correspondence with events and made available to the user.
The model is then able to access data stored in spreadsheets.



Simulation tools: WITNESS® - Modeling

The method by which it is possible to **model a production system** through WITNESS® is presented. In its development we find:

a) elements

WITNESS® provides a long list of predefined elements which, according to needs, can be selected and inserted in the simulation environment. The basic elements of a model in WITNESS® are (figure):

Simulation tools: WITNESS® - Modeling

The method by which it is possible to **model a production system** through WITNESS® is presented. In its development we find:

a) elements

The basic elements of a model in Witness® are:

- **parts**: these are the elements that cross the space-time environment of the model, flowing from the entry position to the final destination. A part can represent a blank, a steel bar, an isolated mechanical detail or a group assembled in successive stages until reaching the finished product state. Parts can be accompanied by a set of attributes;

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Modeling

The method by which it is possible to **model a production system** through WITNESS® is presented. In its development we find:

a) elements

The basic elements of a model in Witness® are:

- **buffers**: they are areas where the parties can stop, accumulate and wait for events before continuing their journey. They limit the rigidity of the system and give the possibility of highlighting anomalous situations. Each buffer is characterized by a capacity, that is, by the number of parts it can contain. It can include a minimum waiting time (for example a cooling down) or a maximum waiting time (for example a deadline);

Simulation tools: WITNESS® - Modeling

The method by which it is possible to **model a production system** through WITNESS® is presented. In its development we find:

a) elements

The basic elements of a model in Witness® are :

- **machines**: are the elements that perform the transformation operations on the parts. The machines are characterized by a cycle time, which represents the duration of the operation, and by rules with ample possibilities for customization to manage the work function. In the personalization of the machine it is possible to introduce elements such as set-up time, the randomness of interruptions in the service (break-down), work shifts and cost elements.

Simulation tools: WITNESS® - Modeling

The method by which it is possible to **model a production system** through WITNESS® is presented. In its development we find:

a) elements

The basic elements of a model in Witness® are:

- The **machines** can be of various types:
  * **single**: if you process one part at a time;
  * **batch**: if one batch is processed at a time;
  * **production**: if a single part is received as input and many are returned, all identical to the original part;
  * **assembly**: if multiple parts are received at the input and only one is returned;
  * **general**: if the number of incoming and outgoing parts can be chosen arbitrarily;
  * **multiple-cycle**: they are a special type of general machine that can simulate multiple separate cycles to complete an operation. Each cycle can have a different number of inlet and outlet parts;
  * **multiple-station**: each of these machines operates as a set of connected machines, having multiple workstations placed in series.

Simulation tools: WITNESS® - Modeling

The method by which it is possible to **model a production system** through WITNESS® is presented. In its development we find:

a) elements

The basic elements of a model in Witness® are:

- **machines**

  Depending on the type of machine, it is possible to define the number of incoming and outgoing parts. The status of a machine during simulation is displayed through a variable color icon:

  - idle: yellow;
  - busy: green;
  - blocked: pink;
  - broken down: red;
  - setting up: azure;
  - waiting(labor): blue;

Simulation tools: WITNESS® - Modeling

The method by which it is possible to **model a production system** through WITNESS® is presented. In its development we find:

a) elements

The basic elements of a model in Witness® are:

- **labors**: these elements can be used to model both human resources and physical resources that constrain the performance of an operation (such as special tools), required by other elements for the processing of the operation, set-up, repair or cleaning of a car etc.;

Simulation tools: WITNESS® - Modeling

The method by which it is possible to **model a production system** through WITNESS® is presented. In its development we find:

b) logistic elements

- **conveyors**: they are used to move the parts between two set points of the model;
- **paths**: they are paths that the parties or operators can follow to move from one element to another;
- **tracks**: these are the paths that vehicles follow when carrying parts. They also define the loading, unloading and parking points;
- **vehicles**: for example AGV (Automatic Guide Vehicle), cranes, forklifts, etc .;

Simulation tools: WITNESS® - Modeling

The method by which it is possible to **model a production system** through WITNESS® is presented. In its development we find:

b) logistic elements

- **attributes**: are the characteristics assigned to specific parts or operators;
- **variables**: these are the values that vary during the model simulation. WITNESS provides numerous system variables including the clock, which provides the simulation time;
- **files**: allow you to upload data relevant to the simulation on the model or, on the contrary, save the data provided by WITNESS®, so that you can use them in other applications;
- **functions**: WITNESS® provides a wide range of predefined functions that can be useful in analyzing the model. You can consult the list of functions available from the Model Assistant window within the software;

Simulation tools: WITNESS® - Modeling

The method by which it is possible to **model a production system** through WITNESS® is presented. In its development we find:

b) logistic elements

- **distributions**: allow to introduce variability in the model by including data from the real world. For example, distributions are used to define the duration of an operation or to manage the breakdown of a machine and subsequently its repair. They are essential in all those cases where the duration of the event is not uniquely determined. WITNESS® offers a wide range of continuous and discrete distributions.

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Modeling

Once the elements have been positioned in the model, **input/output rules** must be established, which define the **entities** through them. The main rules are:

- **PULL**: cause a part to be "pulled" by the previous element (**Input Rule**);
- **PUSH**: cause a part to be "pushed" to the next element (**Output Rule**).

If no rule is set, the program assigns the wait **rule by default** (**wait**). It is also possible to customize the **rules that link the various elements** (**Actions**) using a programming language internal to the program itself.

Simulation tools: WITNESS® - Modeling

The **WITNESS® software** offers great reporting opportunities to highlight situations and transform numerical data into an easily readable form. In fact, it is possible to generate time series, reports, 2D and 3D diagrams, histograms, pie charts and statistical elaborations.

WITNESS® Experimenter is an additional function of the software that allows you to experiment with various scenarios of the model by varying some parameters of it. By opening the Model menu on the main page, selecting Experimenter you can choose two **experimentation modes**:

- a simpler one (**Simple Experimenter Mode**), which allows you to analyze the scenarios for certain sets of parameters;
- a more advanced one (**Advanced Experimenter Mode**), which allows you to set the range of variation of the parameters and to analyze all the scenarios generated by the possible combinations of them.

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Modeling

Clearly the most powerful mode and the one on which attention will focus is the second.

The whole **optimization process** can be summarized in 8 steps:

1) build/open the model you want to optimize with WITNESS® Experimenter;
2) set the goal of the optimization process;
3) quantify the target by translating it into a function;
4) open WITNESS® Experimenter and choose advanced mode;
5) choose the parameters to be changed;
6) fix the properties of the optimization process;
7) start the process;
8) interpret the results.

The main parts of the process will be analyzed in more detail below.

Simulation tools: WITNESS® - Modeling

The preliminary step to be able to start the process is to define a function that quantifies the **objective of optimization** (**objective function**). The variables involved in the definition of the objective function are those that will be optimized (**optimization variables**).

During the optimization process, the evolution of the model is simulated with different combinations of values of the optimization variables and, for each simulation, the objective function is evaluated so as to understand which combination is the best.

Once the WITNESS® Experimenter advanced mode is open, the first thing to do is to define the **parameters of the experimentation**, that is those parameters of the model that will be varied to obtain the optimal configuration.

Simulation tools: WITNESS® - Modeling

Most of the elements in WITNESS® offer a **series of parameters** automatically, for example:

- **parts**: batch size, first arrival time, interactive time;
- **buffer**: quantity, capacity;
- **machines**: quantity, priority, cycle time;
- **conveyor rollers**: quantity, length, maximum capacity;
- **operators**: quantity.

The parameters of interest must be selected, using the Add Parameter key, specifying the Range and the Step size, that is the interval within which the parameters can vary and the step with which they are varied.

WITNESS® Experimenter allows you to set a series of characteristics with which to run the simulation (**Run Properties**). These include the length of the transient (**Warm-up time**), the duration of the simulation (**Run Lenght**) and the number of replicas of the simulation for each configuration (**Replications**).

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Modeling

It is then necessary to define the optimization method to be used; WITNESS® provides a series of methods to choose from, ranging from the simple execution of all possible configurations to more complex and intelligent algorithms. The simplest methods are:

- **All combinations**: it consists in simulating all possible scenarios. It is the best method having all the time necessary to perform the simulation. For complex systems, such as production systems in general, it is not applicable except in some simple cases;
- **Random solutions**: consists of simulating a certain number of scenarios by choosing the parameters randomly. It is not a real optimization method; it can be used at an early stage to evaluate the extent of the solution space;
- **Min/Mid/Max**: this method takes into consideration, for each parameter, only the value, minimum, average and maximum of the variation interval.

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Modeling

Very often the size and complexity of the problem are such that it is not possible to simulate all possible scenarios using the All combinations method. In this case, the so-called heuristic algorithms are used, that is, simply finding a "**good**" **solution** to the problem.

It should be remembered that the term heuristic indicates a method (**algorithm**) for the search for feasible (not necessarily optimal!) solutions of an optimization problem.

Simulation tools: WITNESS® - Modeling

The heuristic algorithms offered by WITNESS® are:

- **Hill Climb**: it is a very simple and fast algorithm, which however often remains "**trapped**" in what is called an excellent venue. The name of this method refers to the ability of the algorithm to "**scale**" the various solutions of the problem towards the best ones. The algorithm, starting from an arbitrary scenario:
  1. analyzes the nearby scenarios, ie those obtained by varying a one-step parameter;
  2. check if one of them produces a better solution than the initial scenario;
  3. if so, start from that scenario by analyzing the neighboring ones.

  The algorithm stops when no change in the parameters leads to an improvement in the solution. In the presence of excellent local solutions it is necessary to use more complex algorithms such as Simulated Annealing;

Simulation tools: WITNESS® - Modeling

The heuristic algorithms offered by WITNESS® are:

- **Simulated Annealing**: as the name suggests (**Annealing**), the basic principle of this algorithm is based on the metallurgical technique of annealing, which consists in melting a material and then cooling it in a controlled manner. At high temperatures the atoms of the material are in a highly disordered state, so the energy of the system is high. Gradual cooling allows to obtain a highly ordered crystalline structure, therefore having minimal energy. Simulated Annealing is the algorithmic analogy of this physical Annealing process. "Rapid cooling" can be seen as analogous to local optimization. The states of the physical system correspond to the solutions of the optimization problem; the energy of a state corresponds to the cost of a solution and the minimum energy corresponds to the optimal solution.

Simulation tools: WITNESS® - Modeling

The heuristic algorithms offered by WITNESS® are:

- **Simulated Annealing**:
  This algorithm can be seen as an extension of the local optimization technique (Hill Climb), in which the initial solution is repeatedly improved through small local perturbations until none of these perturbations improve the solution. The method randomizes this procedure so as to occasionally allow upward movements, that is, perturbations that worsen the solution and this in an attempt to reduce the probability of getting stuck in an excellent room;
- **Six Sigma**: it is based on the Simulated Annealing algorithm, but also allows you to set the maximum number of parameters that can change in the experimentation of each scenario.

Simulation tools: WITNESS® - Modeling

During the experimentation it is possible to follow the processes in real time through various indicators, including:

- the **Run Progress**, which shows an estimate of the time required for completion, the scenarios already analyzed and those missing;
- the **Objective Graph**, which shows the values of the objective function for each scenario and identifies the best result;
- which shows the values of the objective function for each scenario and identifies the best result **Parameter values** relating to the simulated scenario.

Simulation tools: WITNESS® - Modeling

By pressing the results button it is then possible to analyze the results in depth thanks to various tables and graphs:

- **Result Data**: a table containing, for each scenario, the set of parameters that defines it and the average value of the objective function obtained consequently;
- **Box-Plot**: a graph showing for each scenario the minimum, average and maximum value of the objective function obtained in the various replicas, as well as the upper and lower percentile (75% and 25% respectively);
- **Results Chart**: a histogram which represents the average value of the objective function for each scenario;
- **Parameter Analysis**: a table showing the effect that each value of a parameter has on the objective function. In particular, for each value of each parameter the average value of the objective function is calculated and the percentage of improvement (% Benefit) is calculated with respect to the worst value obtained;

Simulation tools: WITNESS® - Modeling

By pressing the results button it is then possible to analyze the results in depth thanks to various tables and graphs:

- **Variance Data**: a table that evaluates the dispersion of the various replicas made for each scenario;
- **Variance Chart**: a chart representing the top ten scenarios of the Variance Data table;
- **Confidence Data**: a table showing the confidence intervals for each scenario;
- **Confidence Chart**: a chart showing the confidence intervals for a selected scenario.

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Optimization of the production system

The term **system** refers to a set of interacting elements cohesive to the achievement of a goal. In particular, a system is characterized by:

- **objectives**: set of purposes that justify the existence of the system;
- **structure**: elements that make up the system and that can be grouped into different subsystems;
- **processes**: activities carried out by the elements of the structure;
- **interrelationship**: relationships between sub-systems, between processes, between the latter and sub-systems.

In general, any type of organization can be described according to a systemic approach specifying its objectives, parts, processes and interrelationships.

Understanding the system thus described will correspond to understanding the behavior of the organization as a whole.

Simulation tools: WITNESS® - Optimization of the production system

The **objectives of a company** are its institutional aims which vary according to the type of company. For a production company, the main objective is to create value, both for customers who satisfy their own utility in acquiring goods, and for themselves, by obtaining a profit from the sale of products.

The **parts of a company** are all the building blocks of the company itself. It is not only the physical elements, but also the organizational units.

The **processes** are all the functions necessary to achieve the operational objectives that the company has set itself and are implemented within the structure. The operational objective of an industrial system is production, that is, the process of transforming raw materials into finished products.

Every **entity** that the company uses in its processes to pursue its operational objectives is a resource. Resources are the products or services offered by the company, the materials used and the properties, but also the money and people used.

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Optimization of the production system

The **study of manufacturing systems** is based on principles or laws, some of which allow us to understand how numerical simulation is an optimal tool for the analysis of these systems and which shows that:

- **systems decay**: in the design of manufacturing systems it must be borne in mind that systems decay, in terms of efficiency and ability to meet demand, like the machinery that compose it. A flexible system designed to last as long as possible will also tend to wear out like obsolete machines;
- the **complexity of the systems grows exponentially**: if a system has m components each of which can be in n different states, then the system has nm possible overall states. Each of them must be considered in the design of the system;

time

Simulation tools: WITNESS® - Optimization of the production system

The **study of manufacturing systems** is based on principles or laws, some of which allow us to understand how numerical simulation is an optimal tool for the analysis of these systems and which shows that :

- **technology improves**: in contrast to the natural decay of systems, technology is continuously improving and what represents the frontier today will be overcome and, therefore, will have to be updated;
- **system components behave randomly**: the operations that are performed will never have the same duration, even if they are exactly the same at each production cycle. Because of the nature of the events, it is difficult to accurately predict the duration of each event. An expected value and a variance can be associated with it;

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Optimization of the production system

The **study of manufacturing systems** is based on principles or laws, some of which allow us to understand how numerical simulation is an optimal tool for the analysis of these systems and which shows that:

- **human rationality is limited**: during decision making, human rationality is limited by various factors including the information it possesses, the cognitive limits of its mind, the finite amount of time it has to make a decision. All this, combined with the exponential growth of the complexity of the systems, highlights the extreme difficulty that arises in the fully rational process of searching for an optimal choice starting from the available information.

Simulation tools: WITNESS® - Optimization of the production system

Once the **logical-mathematical model** that represents the production system has been formulated, to start the optimization process it is necessary to define a goal and subsequently transform it into a function (objective function). In very general terms, an **optimization problem** can be formulated as follows:

$$\max f(a) \qquad with \qquad a \in A$$

where A is the finite set of alternatives, "**a**" is the **generic alternative** and the function f (a) is the objective function that expresses the usefulness of the decision "a" for the decision maker. The problem consists in determining an **alternative to a* optimal** for which we have:

$$f(a) \leq f(a^*) \qquad \forall a \in A$$

Note that having written max f(a) is by no means restrictive since a minimization problem can be traced back to a maximization problem simply by changing the sign of the objective function (and vice versa).

Simulation tools: WITNESS® - Optimization of the production system

Since the number of elements of the set A is finite, the problem is conceptually trivial: **it is a matter of examining all the alternatives and selecting the best one**. From a computational point of view, however, this way of proceeding, which is called an **exhaustive method**, can only be used when the number of alternatives is very limited. In the opposite case, that is, when the number of alternatives is high, some particular optimization method must be used.

Very often the size and complexity of the problem are such that, even with the aid of an effective optimization method, it is not possible to determine with certainty the optimal solution of the problem. In this case, a **heuristic method** is used, that is, we simply look for a **"good" solution to the problem**.

There can be the case in which the solution determined through the heuristic method is also excellent, but the very nature of the method does not provide guarantees in this sense.

Numerical simulation as a tool for optimizing a production system

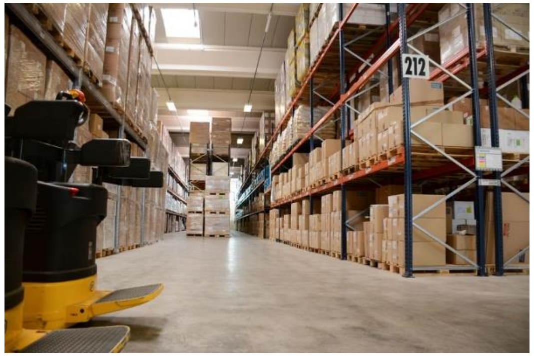
Simulation tools: WITNESS® - Optimization of the production system

Given the complexity of the production systems, the need for a software tool that does the computational work is evident.

The optimization process is developed in WITNESS®.

In a production organization, Simulation-based Optimization techniques can refer to an extremely wide range of problems, among which, by way of example, we can mention:

a) **design, sizing and regular verification of production systems and various system components** such as:
   - component, semi-finished and finished product warehouses;
   - interoperational buffers;
   - handling systems;
   - work stations;



Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Optimization of the production system

In a production organization, Simulation-based Optimization techniques can refer to an extremely wide range of problems, among which, by way of example, we can mention:

b) study of the behavior of the system with the variation of:

- production mix;
- production volume;
- labor performance;
- work cycles;
- scheduling strategies;

c) factory logistics management with:

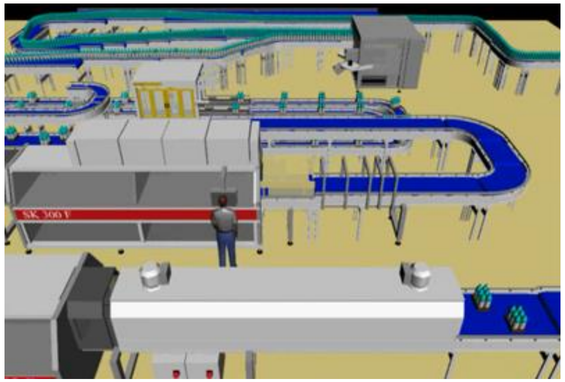
- verification of procurement policies and their effects on production and financial assets within the plant;
- verification between the various maintenance policies of the plants and relations with the distribution and commercial subsidiaries.

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Optimization of the production system

Through **simulation**, we tend to try to optimize the production flow, handling, logistics and information flow, eliminating discontinuities and traffic jams as much as possible, through the identification and elimination of bottlenecks.

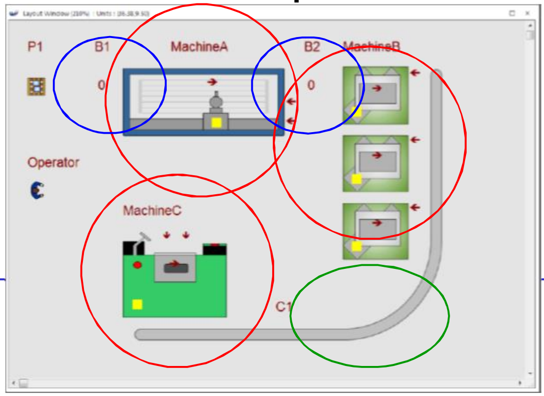
We will now analyze an example of the configuration of a simple production line and how it is possible, through simulation techniques, to identify the optimal configuration.



Simulation tools: WITNESS® - Optimization of the production system

A generic production line consisting of:

- 3 different types of machines (1 machine A, 3 machines B in parallel, 1 machine C). It was decided to name the machines with letters, without specifying the type of processing, because modeling does not depend on this. Whatever the operation carried out by the machine, what matters is only knowing the parameters involved in the simulation (cycle time, machine blocks, etc.);
- 2 accumulation buffers (one input before machine A and one between machine A and machines B) with a capacity of 90 parts;
- 1 conveyor roller connecting machines B and C capable of transporting a maximum of 25 parts at a time, one operator and one part.



Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Optimization of the production system

The part, that is the piece to be worked on, enters the system with an interactive time of 5 s, passes through the system, undergoes a series of operations and exits.

Given the presence of stochastic events, it is necessary to carry out a preliminary data collection to have the probability distributions relating to the various events, distributions essential for modeling the system. In the specific analysis it is considered to have already carried out this phase and to have identified probability distributions for the following stochastic events:

- cycle time of the various machines;
- breakdown of the various machines.

In particular, for the cycle time of the various machines we consider:

- machine A: uniform distribution between 2.75 s - 4.00 s;
- machine B: uniform distribution between 5.00 s - 15.00 s;
- machine C: normal distribution with average 3.75 s and variance 0.25 s.

Simulation tools: WITNESS® - Optimization of the production system

Indicating with:

- **mode**: the fact that the machine lockout may occur based on the number of operations or on the basis of the time of use of the machine (busy time);
- **N. oper.**: specifies the number of operations;
- **T. in beak**: machine use time between two successive breakdowns;
- **T. ripar.**: time required to restart the machine (repair time);

for blocking from the machines the table values are provided.

Breakdown	Mode	N. oper.	T. tra break.	T. ripar.
A: Head/tool failure	n. oper.	50	-	10
A: Mount failure	n. oper.	150	-	Uniform(30,60)
B: Tool failure	t. di lavoro	-	Uniform(120,180)	Uniform(10,15)
C: Tool failure	n. oper.	Uniform(30,50)	-	Uniform(20,40)
C: Tolerance failure	t. di lavoro	-	Uniform(100,300)	Uniform(10,15)

Characterization of machine blocks

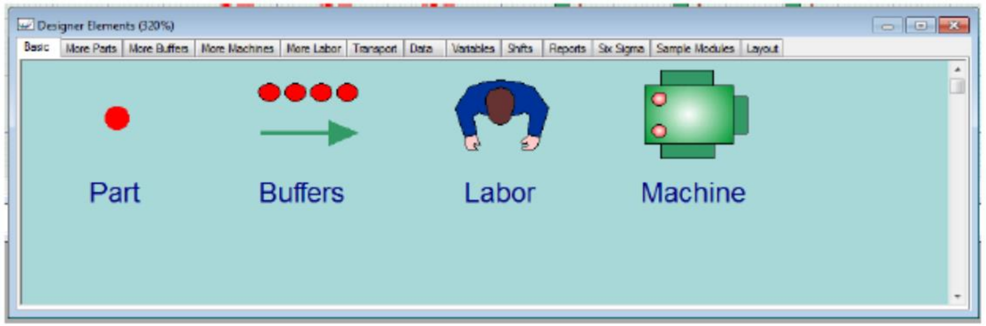
Simulation tools: WITNESS® - Optimization of the production system

Modeling a production system using WITNESS® is particularly easy. The procedure followed to model the production line under study is illustrated below, highlighting its simplicity:

a) insertion of the basic elements

The insertion of the basic elements that make up the model takes place by dragging the elements of interest from the Designer Elements window to the Windows Layout window which represents the model seen in 2 dimensions. In the case in question, we insert:

- 1 part: P1
- 2 buffers: B1, B2
- 3 machines: A, B, C
- 1 conveyor roller: C1
- 1 operator



arranging them as specified in the description of the line;

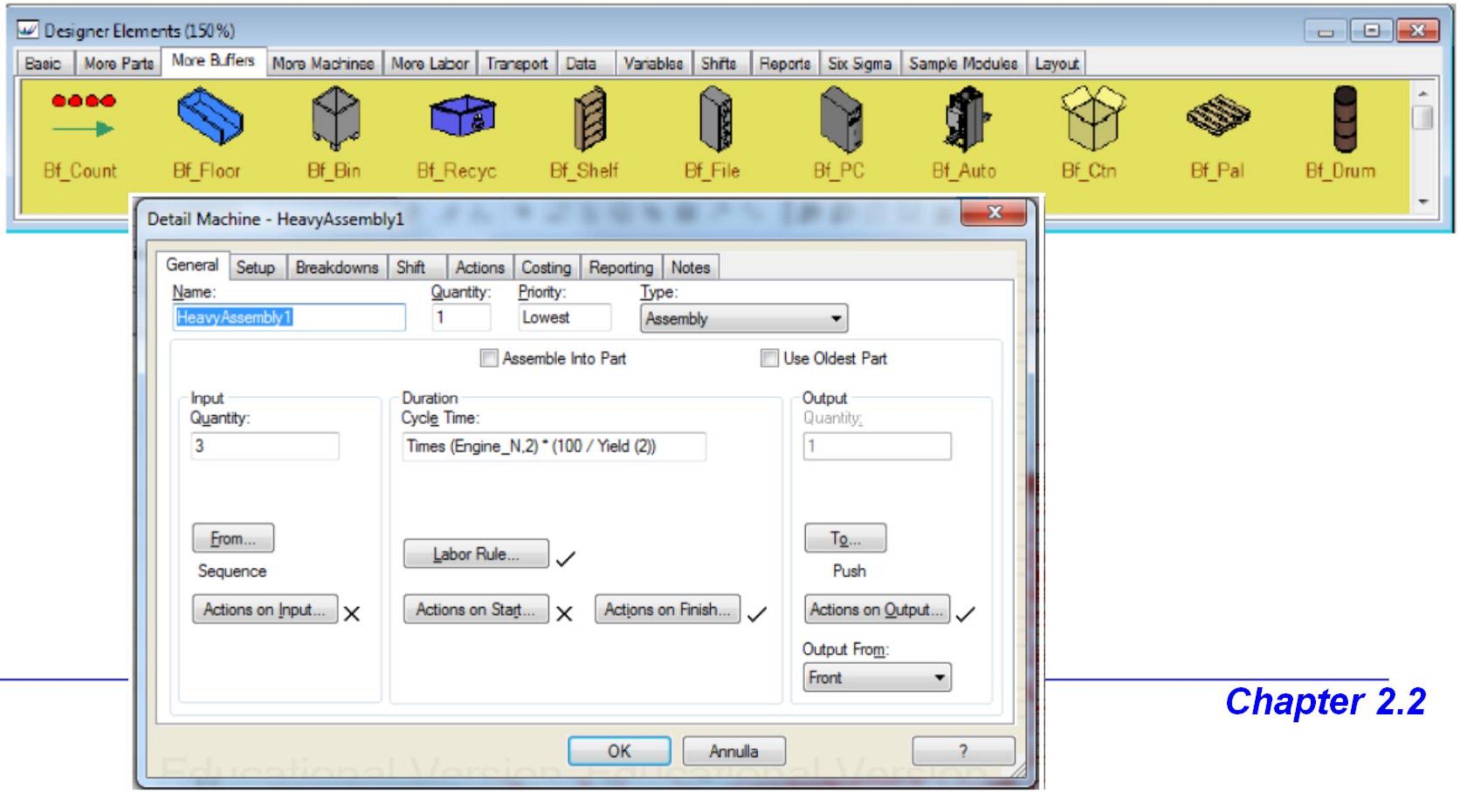
Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Optimization of the production system

Modeling a production system using WITNESS® is particularly easy. The procedure followed to model the production line under study is illustrated below, highlighting its simplicity:

a) **insertion of the basic elements**

Machine



Simulation tools: WITNESS® - Optimization of the production system

The procedure followed to model the production line under study is illustrated below, highlighting its simplicity:

b) insertion of logistic elements

Always starting from the Designer Elements window it is possible to insert logical elements, such as variables and functions. To optimize the line, we act on the buffer capacities and the dimensions of the conveyor roller, for this reason the following variables are introduced by initializing them:

- B1Cap = NFree (B1) Current unused capacity of Buffer B1
- B2Cap = NFree (B2) Current unused capacity of Buffer B2
- ii = NFree (C1) Current unused capacity of roller C1

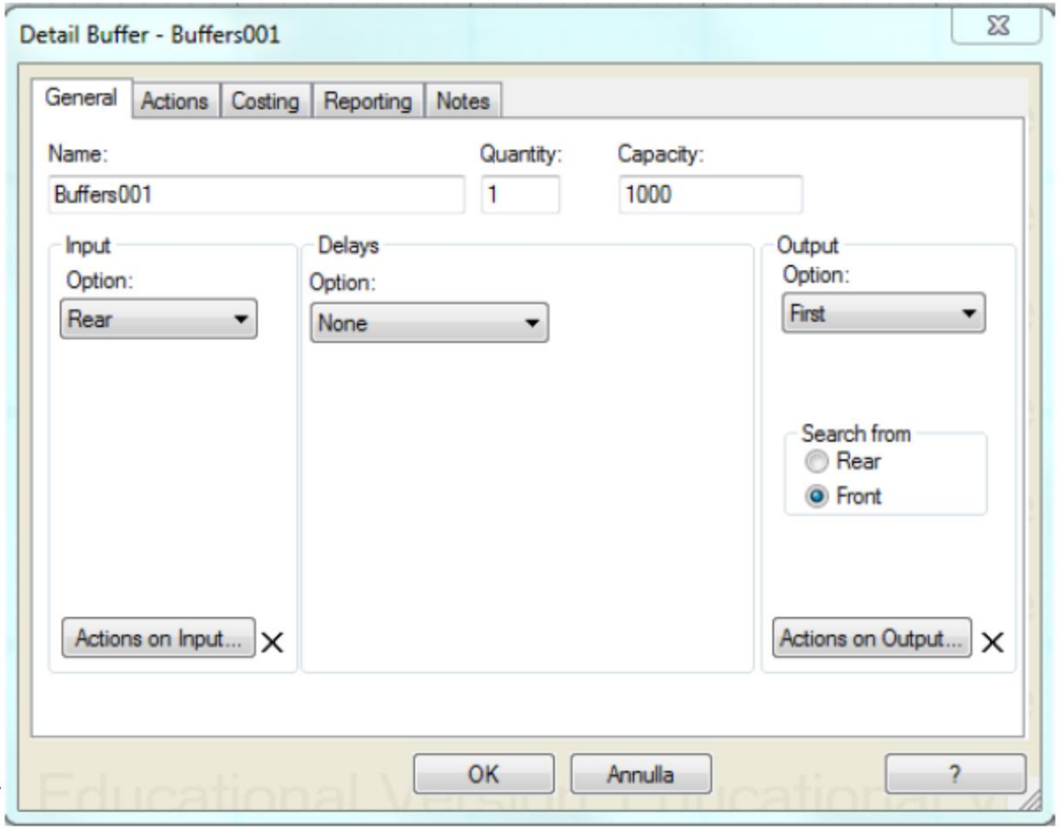
To initialize the variables, the NFree() function made available by the software was used. These variables will be used in the definition of the objective function;

Simulation tools: WITNESS® - Optimization of the production system

The procedure followed to model the production line under study is illustrated below, highlighting its simplicity:

b) insertion of logistic elements

Buffers



Simulation tools: WITNESS® - Optimization of the production system

The procedure followed to model the production line under study is illustrated below, highlighting its simplicity:

c) definition of the details of the basic elements

After arranging the elements in the Windows Layout window, it is necessary to enter the various basic parameters for the simulation (arrival times of the parts, cycle times of the machines, machine blocks, etc.). By double-clicking on each element, opening the detail window, you enter the values specified in the description of the line, in particular:

- the interactive time of the parties (Inter Arrival Time)
- the cycle time of the various machines
- breakdowns and repair times for the various machines
- the number of machines B
- the buffer capacities before optimization
- the dimensions of the conveyor roller before optimization;
- using, if necessary, probability distributions made available;

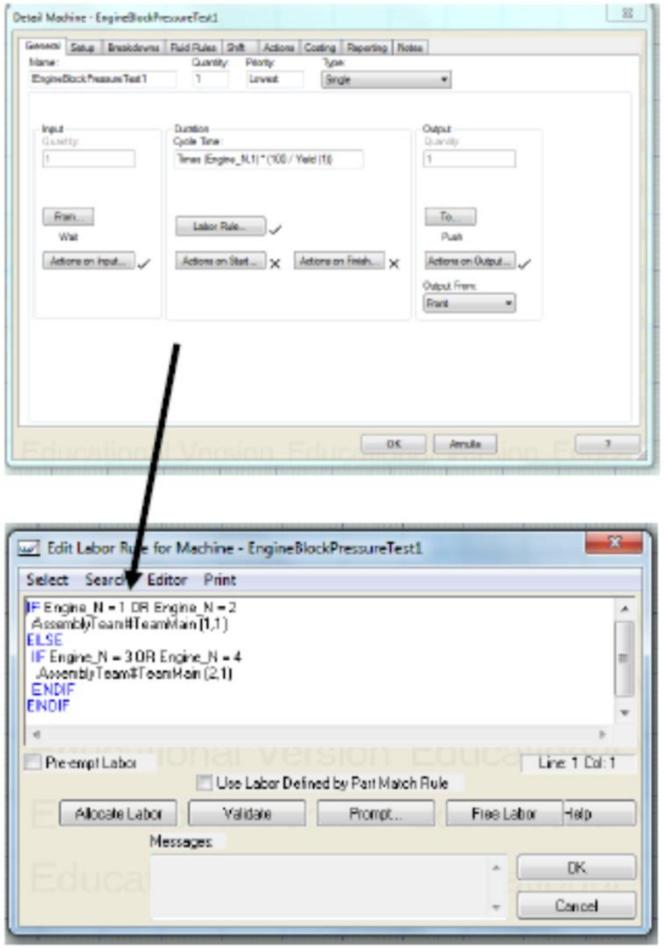
Simulation tools: WITNESS® - Optimization of the production system

The procedure followed to model the production line under study is illustrated below, highlighting its simplicity:

d) links between elements

To conclude the modeling of the line, it is necessary to connect the various elements with rules (rules). By double-clicking on the various elements, opening the detail window for each of them insert the following Input/Output Rules:

- Part P1
- Output Rules: PUSH to B1
- Machine A
- Input Rules: PULL from B1
- Output Rules: PUSH to B2



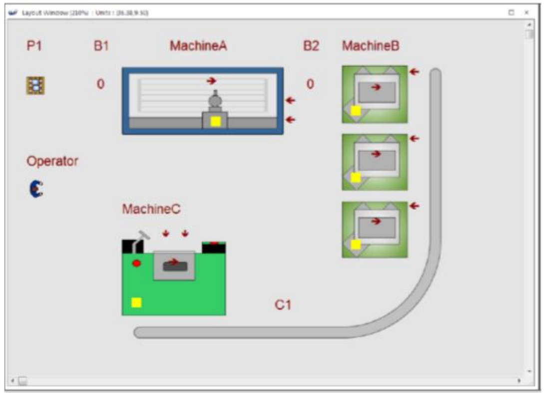
Simulation tools: WITNESS® - Optimization of the production system

The procedure followed to model the production line under study is illustrated below, highlighting its simplicity:

d) connections between elements

To conclude the modeling of the line, it is necessary to connect the various elements with rules (rules). By double-clicking on the various elements, opening the detail window for each of them insert the following Input/Output Rules:

- Macchina B
  Input Rules: PULL from B2
  Output Rules:
  IF N = 1
  PUSH to C1 at Rear
  ELSEIF N = 2
  PUSH to C1 at (ii - 4)
  ELSE
  PUSH to C1 at (ii - 8)
  ENDIF

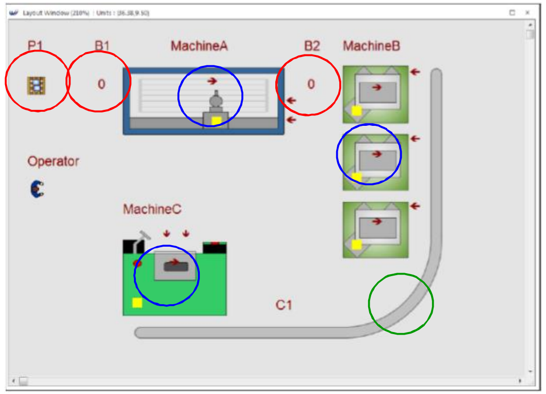


Simulation tools: WITNESS® - Optimization of the production system

The procedure followed to model the production line under study is illustrated below, highlighting its simplicity:

d) connections between elements

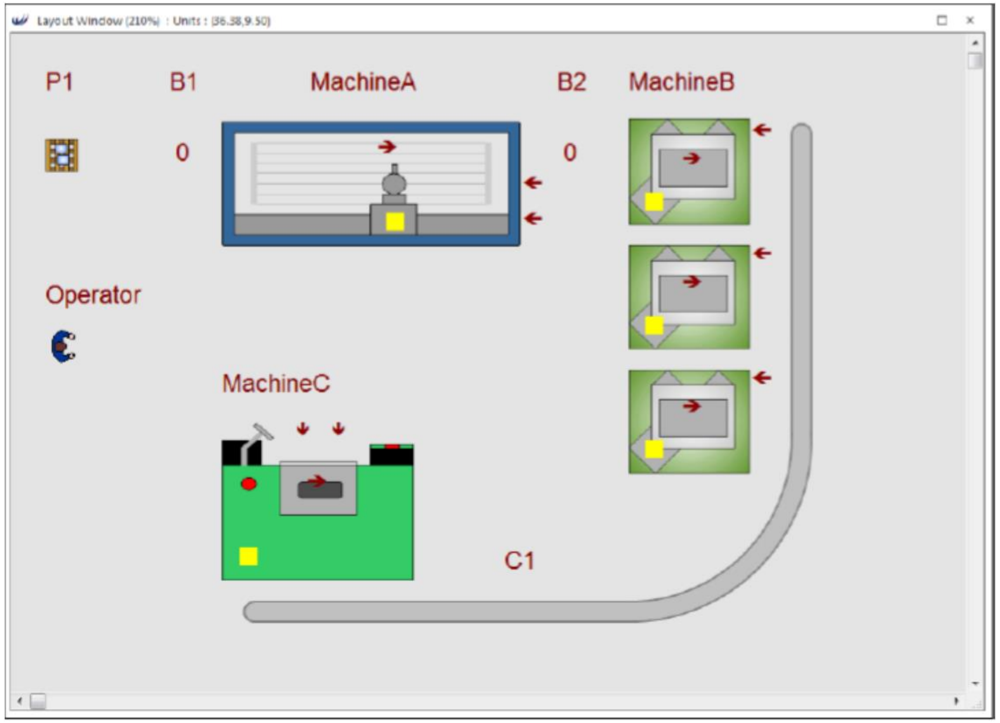
In this way the movements of the parts through the model were imposed. In particular, a part P1 enters the model (with an interactive time of 5 s), is "pushed" into buffer B1; here it is "pulled" by machine A which carries out its own processing and "pushes" it into buffer B2. Then it is pulled again into one of the 3 machines B, which carries out its processing and "pushes" it onto the conveyor roller C1, in a position which depends on the machine that performed the operation (figure). The part is transported along the entire roller until it reaches a position close to the machine C, which "pulls" it, performs the processing and exits the system.



Simulation tools: WITNESS® - Optimization of the production system

The procedure followed to model the production line under study is illustrated below, highlighting its simplicity:

d) connections between elements



Production line model in WITNESS®

Simulation tools: WITNESS® - Optimization of the production system

The production line modeling is complete. We will now show how to optimize it using the tools made available by WITNESS® Experimenter.

The preliminary step of each optimization process is the identification of a goal and its translation into a function (**objective function**). The goal is to obtain the largest number of pieces (**parts**) with the lowest possible cost. The objective function must include a positive term for the number of pieces that leave the model (**ship**) and negative terms that take into account the costs due to labor and the size of the line.

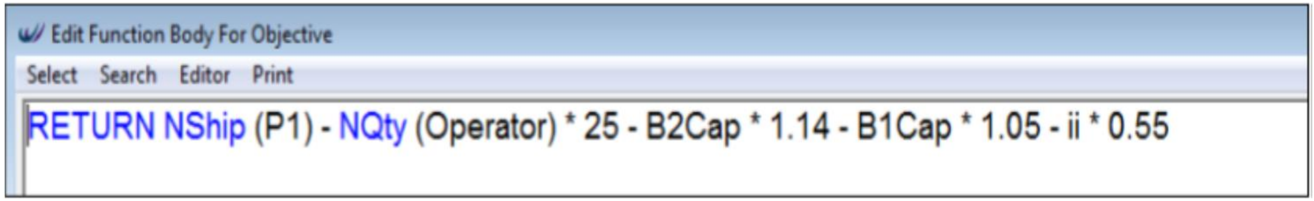
The line variables considered for the purpose of formulating the objective function (**Optimization variables**) are:

- the current unused capacity of buffers B1 and B2 (B1Cap, B2Cap);
- the current unused capacity of the conveyor roller (ii);
- the number of operators (NQty (operator)).

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Optimization of the production system

Multiplying coefficients are assigned to these variables based on the costs associated with them. In this way the objective function is defined (figure).



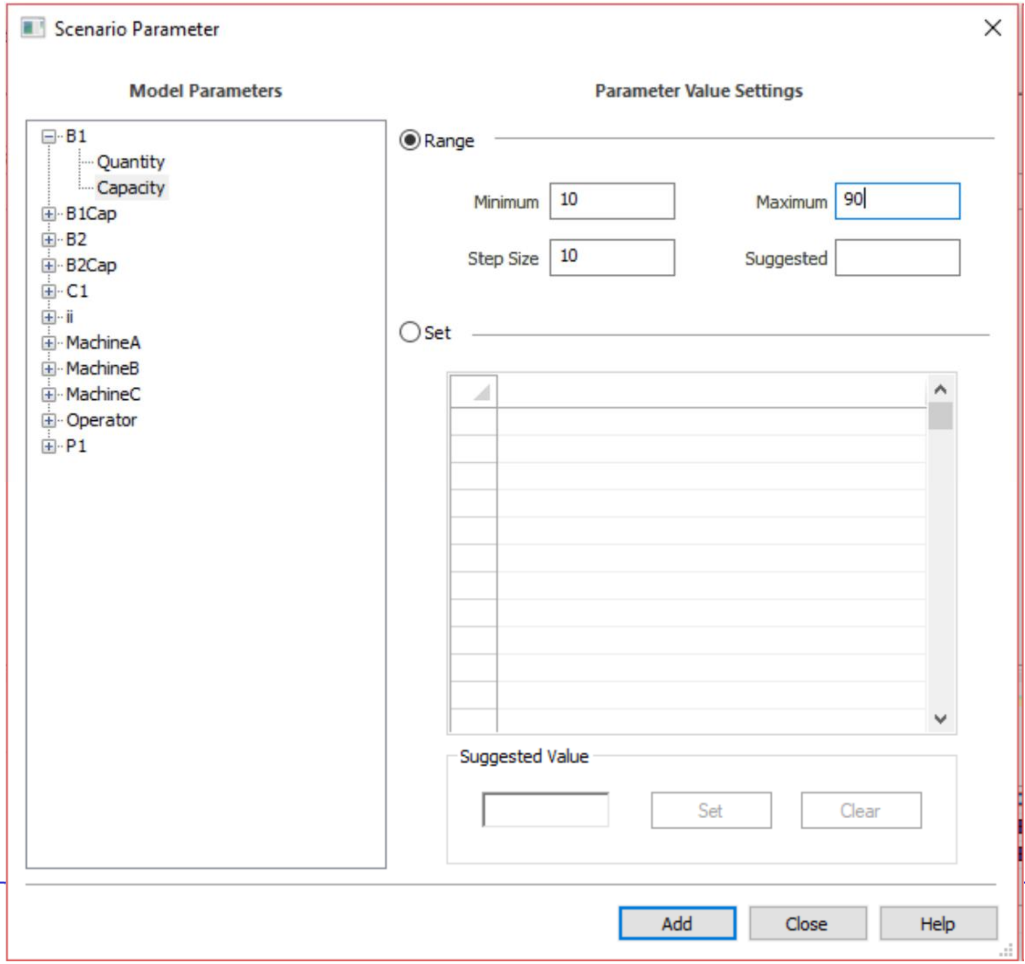
By opening WITNESS® Experimenter in Advanced Experiment Mode it is possible to define the range of variation of the various decision parameters. In the case in question, the table parameters are set.

Parameter	Range	Step Size
Number of operators	1 - 3	1
Buffer capacity B1 and B2	10 - 90	20
Length of the conveyor roller	25 - 45	10

Decision parameters

Simulation tools: WITNESS® - Optimization of the production system

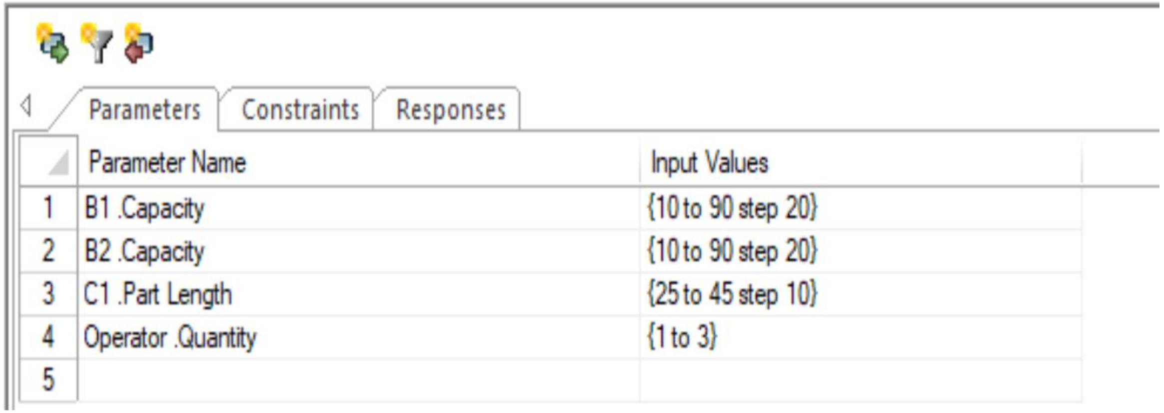
To do this, simply press the add parameter button, select the parameter of interest and enter the previous values (figure).



Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Optimization of the production system

Having entered all four parameters at the end you get what is shown in the figure where the display of the scenario manager is shown.



	Parameter Name	Input Values
1	B1 .Capacity	{10 to 90 step 20}
2	B2 .Capacity	{10 to 90 step 20}
3	C1 .Part Length	{25 to 45 step 10}
4	Operator .Quantity	{1 to 3}
5		

The next step is to insert the previously defined objective function. To do this, just click the ñadd responseò button and select it. Before being able to start the experimentation it is necessary to establish the modalities (run properties) with which to perform it.

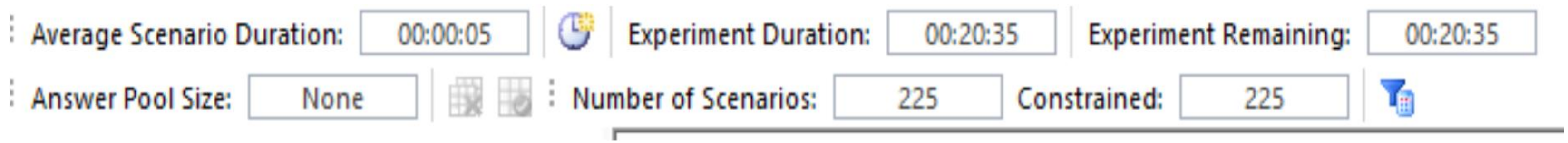
Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Optimization of the production system

In the window with figures are fixed:

- duration of the transient (Warm-up): 60 s
- duration of the simulation (Run Length): 14400 s
- repetitions for each scenario (Replications): 10
- objective function (Objective): Objective
- target: Maximum
- Optimization Method: All combinations

In the toolbar it is possible to notice some useful information including the estimated time to complete the experimentation and the number of different scenarios generated by the variations of the set parameters (figure).



Information about the ongoing optimization process

Simulation tools: WITNESS® - Optimization of the production system

Although the analyzed production system is very simple and the number of parameters limited, the number of scenarios generated is high (225), especially if one takes into consideration the fact that each scenario is simulated several times to obtain a reliable estimate of its behavior.

For example, if you choose to replicate each scenario 10 times, the program will have to perform 2250 simulations! In this simple example, we highlight the need for optimization algorithms that allow to carry out the process without necessarily having to analyze each individual scenario, thus reducing the time required for experimentation.

Given the relative simplicity of the line, one could proceed by evaluating all possible combinations; however, we will initially proceed using the Simulated Annealing method, the method generally most used in the optimization of production systems, and only at the end will the All combinations method be used. This will allow to compare the two optimal solutions obtained, so as to verify the potential of the heuristic algorithm.

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Optimization of the production system

By choosing the Simulated Annealing (SA) optimization method, the software allows you to vary many settings that determine the execution of the algorithm.

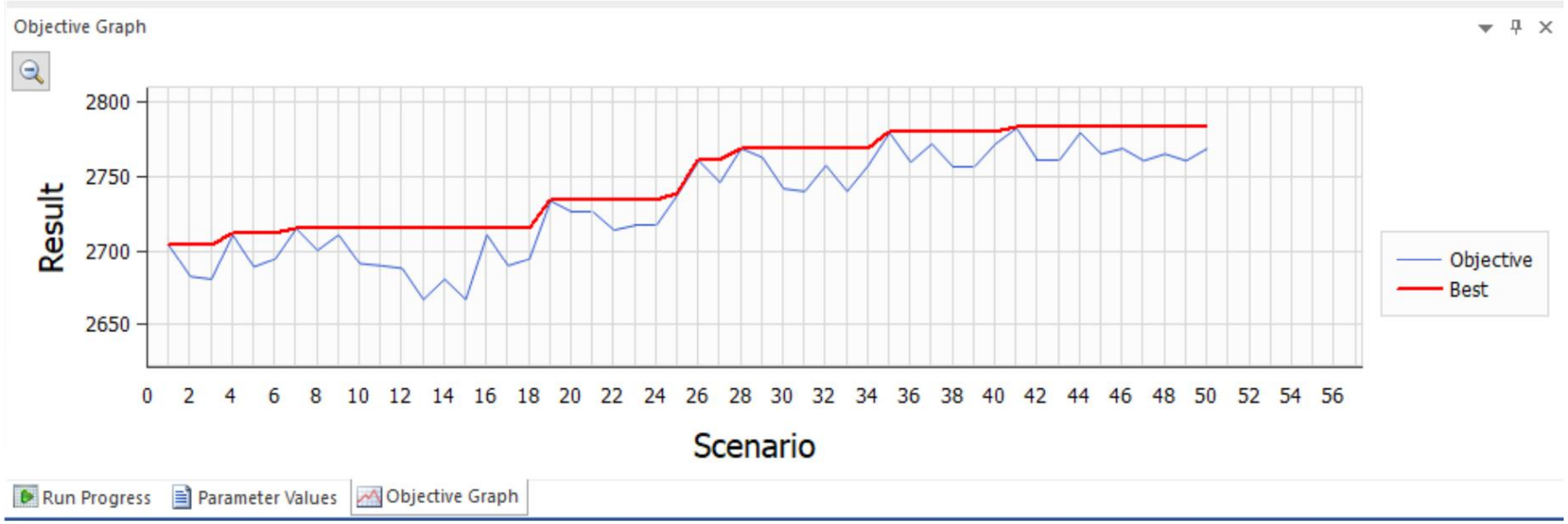
For the analysis carried out, the following was established:

- maximum number of scenarios: 50
- maximum number of movements without improvement: 50

Starting the experimentation, the software proceeds with the simulation of the various scenarios providing, at the end of the process, multiple tables and graphs to analyze the results.

Simulation tools: WITNESS® - Optimization of the production system

As you can see from the **Objective Graph** (figure), the SA algorithm proceeds with the simulation of the various scenarios, starting from a randomly chosen scenario, gradually identifying those that produce the best results.



Objective Graph for the various scenarios

Simulation tools: WITNESS® - Optimization of the production system

From the **Results Data** (figure), ordered in descending order with respect to the **Objective function**, we obtain the scenario that produced the optimal result.

	Scenario	Objective	B1 .Capacity	B2 .Capacity	C1 .Part Length	Operator .Quantity
1	41	2782.950	30	10	25	1
2	35	2779.850	30	10	35	1
3	37	2772.350	30	10	45	1
4	28	2769.250	30	10	25	2
5	45	2765.550	10	10	25	1
6	29	2763.250	30	10	35	2
7	26	2761.050	30	30	25	1
8	36	2760.050	10	10	35	1
9	32	2757.850	30	10	45	2
10	38	2756.850	30	30	35	1
11	27	2746.450	30	30	25	2
12	30	2742.250	50	10	35	2
13	31	2740.450	30	30	35	2
14	25	2738.250	30	50	25	1
15	19	2734.050	30	50	35	1
16	20	2726.750	30	50	45	1

Results Data | Box-Plot | Results Chart | Parameter Analysis | Va

Results Data

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Optimization of the production system

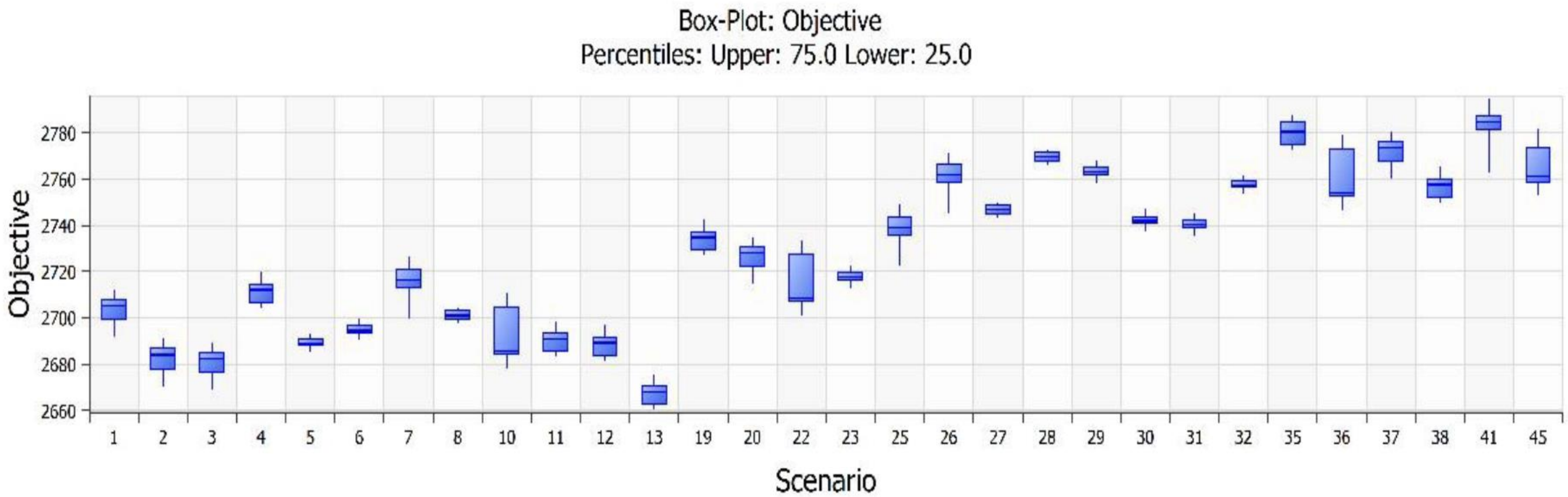
The optimal configuration of the production line in question, with respect to the parameters considered, is that shown in the table

Parameter	Value
Number of operators	1
Buffer capacity B1	30
Buffer capacity B2	10
Length of the conveyor roller	25

From the table of Results Data you can also read the value of the objective function (2782.950); this value represents the average of the values of the function, obtained in the various iterations of the simulation of each scenario (10 in the case under examination). It should be remembered that given the presence of variability in the system, the results obtained are never exact results, but rather statistical estimates. For this, the greater the number of iterations made, the more reliable the estimate will be.

Simulation tools: WITNESS® - Optimization of the production system

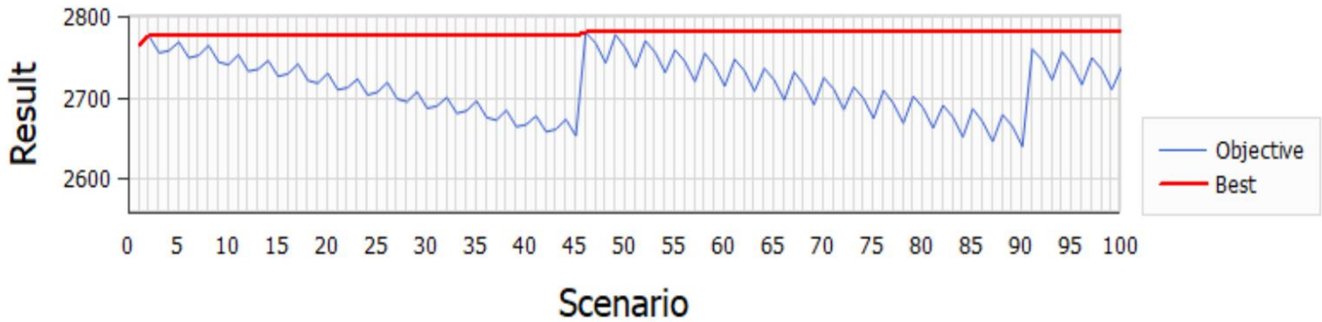
From the **Box-Plot** graph, shown in the figure, it is possible to view the dispersion of the results for the different scenarios.



Given the relative simplicity of the line, the number of scenarios, although high, can also be analyzed with the All Combinations method, accepting a higher computational cost. In the following we have used this method to verify the effectiveness of the Simulated Annealing algorithm used previously.

Simulation tools: WITNESS® - Optimization of the production system

From the execution of the experimentation for all the possible scenarios we have reached the same optimal configuration as that obtained with the heuristic algorithm (figure and table); this confirms the effectiveness of this algorithm.



Objective-Graph function for the various scenarios with the All Combinations method

Simulation tools: WITNESS® - Optimization of the production system

From the execution of the experimentation for all possible scenarios, we have reached the same optimal configuration as that obtained with the heuristic algorithm (figure and table); this confirms the effectiveness of this algorithm.

	Scenario	Objective	B1 .Capacity	B2 .Capacity	C1 .Part Length	Operator .Quantity
1	46	2782.950	30	10	25	1
2	49	2779.850	30	10	35	1
3	2	2777.950	10	10	25	2
4	52	2772.350	30	10	45	1
5	5	2770.850	10	10	35	2
6	47	2769.250	30	10	25	2
7	8	2766.550	10	10	45	2
8	1	2765.550	10	10	25	1
9	50	2763.250	30	10	35	2
10	91	2761.950	50	10	25	1
11	55	2761.050	30	30	25	1
12	4	2760.050	10	10	35	1
13	94	2758.850	50	10	35	1
14	53	2757.850	30	10	45	2
15	3	2757.450	10	10	25	3
16	58	2756.850	30	30	35	1

Results Data | Box-Plot | Results Chart | Parameter Analysis | V

Results Data with All Combinations method

Simulation tools: WITNESS® - Optimization of the production system

Following the simulation of the production line to the WITNESS® optimization functions, it was possible to identify the optimal configuration of the line that **maximizes** the **defined objective function** (figure).

Edit Function Body For Objective

Select Search Editor Print

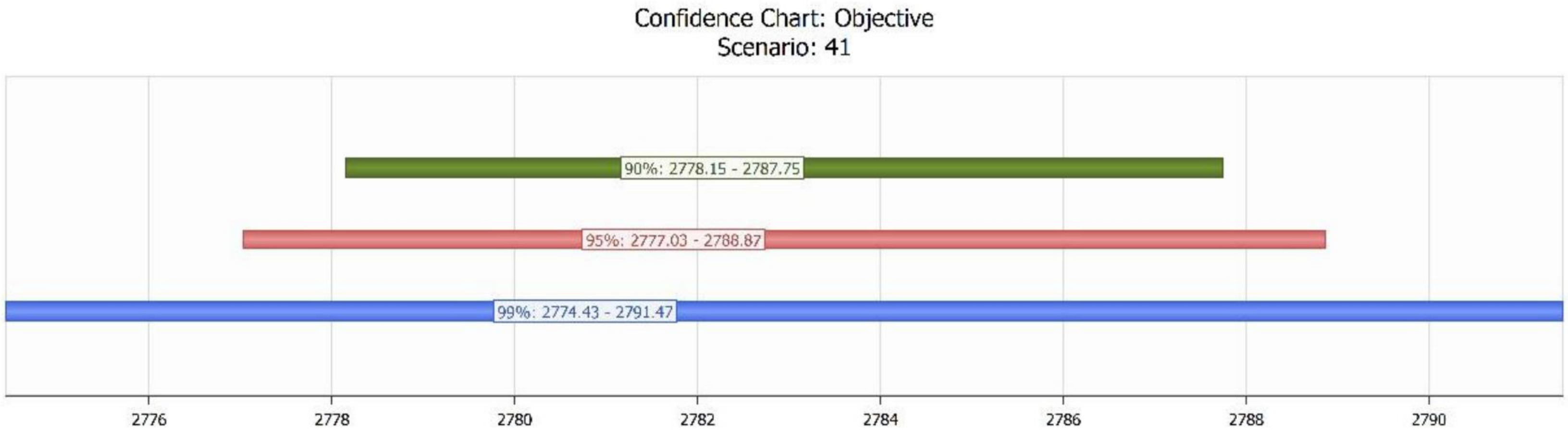
```
RETURN NShip (P1) - NQty (Operator) * 25 - B2Cap * 1.14 - B1Cap * 1.05 - ii * 0.55
```

The **optimal configuration**, based on the simulations carried out, is shown in the table

Parameter	Value
Number of operators	1
Buffer capacity B1	30
Buffer capacity B2	10
Length of the conveyor roller	25
Average target function value	2782.950

Simulation tools: WITNESS® - Optimization of the production system

The obtained value of the **objective function**, average of the values obtained in the various iterations of the simulation, must be considered exclusively as a statistical estimate. The value that will be obtained in reality will never be the same as that obtained. For this reason, it is more significant to refer, instead of to the point value, to the confidence interval in which the real value has a high probability of falling back. The graph of the figure shows the 90%, 95% and 99% confidence intervals for the optimal scenario.



Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Final thoughts

The conclusions that can be drawn from the objectives set correspond to:

- **acquisition of basic knowledge of simulation technique;**
- **acquisition of the basic principles of the Simulation-Based Optimization technique;**
- **use of the WITNESS® simulation software (Manufacturer Performance Edition version) in the implementation, simulation and optimization of models relating to production systems;**
- **application of the simulation tool to a simple example.**

Numerical simulation as a tool for optimizing a production system

Simulation tools: WITNESS® - Final thoughts

- The first **two points (acquisition of basic knowledge of simulation technique and of the basic principles of the Simulation-Based Optimization technique)** were fundamental for understanding the basic principles, potentials and limitations of these techniques. The **third point (use of the WITNESS® simulation software (Manufacturer Performance Edition version) in the implementation, simulation and optimization of models relating to production systems)** allowed to analyze the functioning of one of the most popular simulation software, allowing to highlight the following considerations:
- the use of simulation software and, in particular, the version dedicated to production systems, allows to simplify considerably the implementation of simulation models;

Simulation tools: WITNESS® - Final thoughts

the integration of optimization tools within a simulation program allows a more in-depth analysis of the system under study, allowing to identify the best design or operational choices, thus representing the ideal tool to support the decision-making process.

The **fourth point (application of the simulation tool to a simple example)** allowed to apply, albeit limited to its simplicity, the tools learned in the previous points, making it possible to specifically identify the critical points that arise in the application of the simulation tool. In particular, the following considerations are highlighted:

- in order to adequately model a production system, it is very important to have historical data available for those variables that have a decisive role in the model such as machine breakdowns, stops and retooling times, for all those variables that introduce the random element;

Simulation tools: WITNESS® - Final thoughts

The **fourth point (application of the simulation tool to a simple example)** allowed to apply, albeit limited to its simplicity, the tools learned in the previous points, making it possible to specifically identify the critical points that arise in the application of the simulation tool. In particular, the following considerations are highlighted:

- from carrying out the simulation experiments it was found that the machine time necessary for the analysis of possible scenarios is a critical element in optimizing a production system. In the case in question, although only four parameters had been set, which vary limitedly, the time taken to test all the scenarios was more than an hour. In more complex production systems, such as those normally found in manufacturing industries, the need to use algorithms that allow to reduce the computational cost is evident.