UNIVERSITAT POLITÈCNICA DE CATALUNYA
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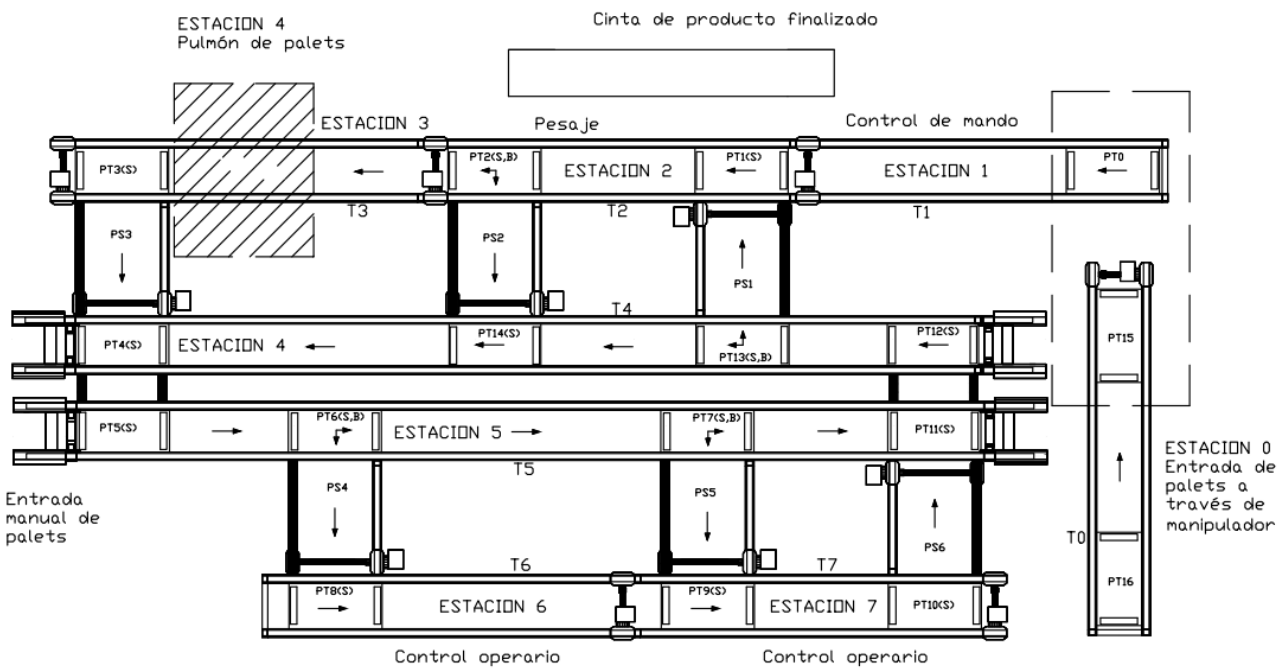

MASTER THESIS

Industrial process simulation for manufacturing performance assessment

Erasmus Exchange Program: Master's in Engineering Technology Management

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1) ABSTRACT :

Industrial process simulation for manufacturing process assessment

As the industrial requirements change at an important pace due to the evolution of Technology and the digitalization of Manufacturing and Production operations, the necessity of investigating potential alternatives toward more efficient industrial line design arises more intensely than ever. The urge towards the digitalization of production in the context of the industry 4.0 framework has shaped the rise of simulation in the design and operation of manufacturing systems.

Industrial system simulation is a power tool for designing and evaluating the performance of manufacturing systems, due to its low cost, low risk, and quick analysis and insight that it provides.

This paper studies the usage of simulation models and ARENA simulation software in the analysis and simulation of an industrial manufacturing line located in lab TR2 at UPC, using Discrete Event System technique, which is based on queue theory. This paper proposed a methodic method and steps used for modelling the lined by using DES technique, which describes a system response in occurrence of an event possibly required to meet certain conditions. Finally, the paper addresses the improvement opportunity on the retainers of the line to better its production capacity.

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3) LIST OF ABREVIATION :

DES : Discrete Event Simulation

MCS : Monte Carlo Simulation

UPC : Universitat Politecnia Catalunya

WIP: Work In Progress

FIFO: First In First Out

ATM: Automated Teller Machine

POS: Position

PLC: Programmable Logic Controller

TFM : Trabajo de Fin de Master

4) PROJECT INFORMATION :

a) Aim of the project :

The aim of this project is to assess the performance of an industrial line. This analysis will be performed using a simulation methodology. The conveying line in lab TR2 at UPC is the manufacturing process line available for this study.

The objective of this study is the creation and simulation of the manufacturing line setup in lab TR2 0.04. This line is based on the automatic activation of a series of conveyor belts for the management of a predefined process or application. The basic movement is the transport of a plate between different conveyors. Another objective is the identification of the manufacturing line limitation and improvement opportunities.

The setup in the lab contains many components such as motors, sensors, stoppers, and platforms. The figure below gives an overview of the components and their location:

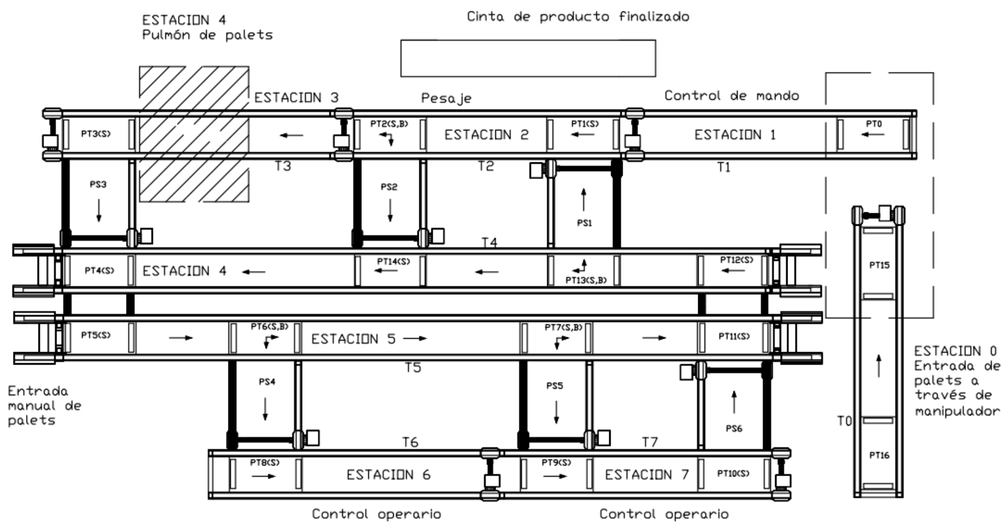


Figure 1 : overview of the manufacturing line in lab

b) Scope :

In regard with the aim of this project, the scope includes:

- Study and understanding of the available industrial line at school facilities
- State of the art in industrial processes modelling and simulation
- Selection and determination of parameters considered for the simulation of the process

- Implementation of the simulation model based on Arena software

- Definition of test vectors and validation of the model

- Identification of manufacturing line limitations and improvement opportunities

- Documentation and presentation

c) Requirements :

ARENA simulation software is used to create a model for the manufacturing line. It is a discrete event simulation and automation software developed by Systems Modeling and acquired by Rockwell Automation in 2000. In ARENA, the user builds and experiment model by placing modules (boxes of different shapes) that represent processes or logic. Connector lines are used to join these modules together. Statistical data, for instance the cycle time and WIP (work in progress), can be recorded on reports. ARENA allows the functions needed for simulation: modelling, animation, model verification, analysis of inputs and outputs data, results of analysis.

ARENA can be used to model any system within the manufacturing or service industries. Examples include logistics operations, Supply Chain, Vehicle planning and scheduling, etc.

For this project, the student Edition is used. This version is similar to the commercial version but limited in model size (less than 150 entities going through the model at the same time).

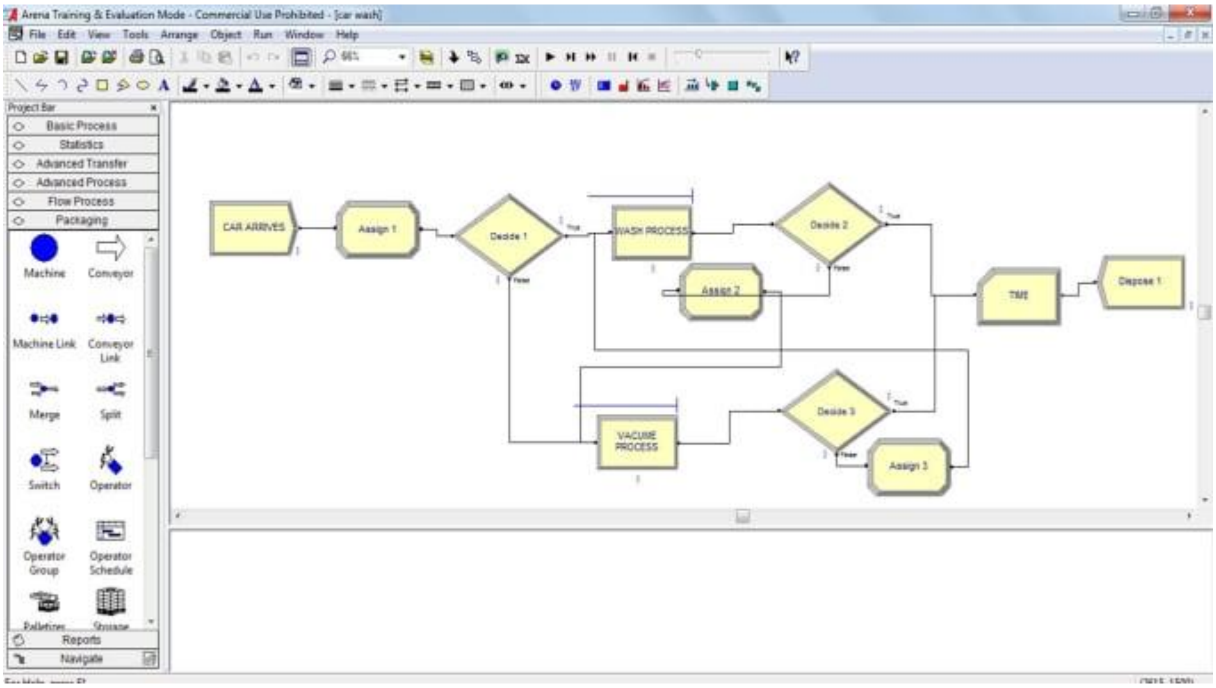


Figure 2 : overview of the ARENA interface

5) INTRODUCTION :

Mathematical models are used in the natural sciences, engineering disciplines, as well as in the social sciences, for understanding the static and dynamic behavior of physical processes. They are also used to compare alternative system configurations or to predict future behavior. Finally, for evaluation and testing real processes, for instance in Manufacturing.

In brief, a conceptual model of a system is a structural representation used to help to know, understand, and simulate its behavior. It allows for investigation of the properties of the system and, in some cases, prediction of future outcomes.

Models are necessarily incomplete because it is a representation. No model includes every aspect of the real world. To create a model, it is necessary to make some assumptions about the essential structure and relationships of objects and events in the real world. Moreover, models are always a compromise between simplicity and the need to include the systems relevant aspects.

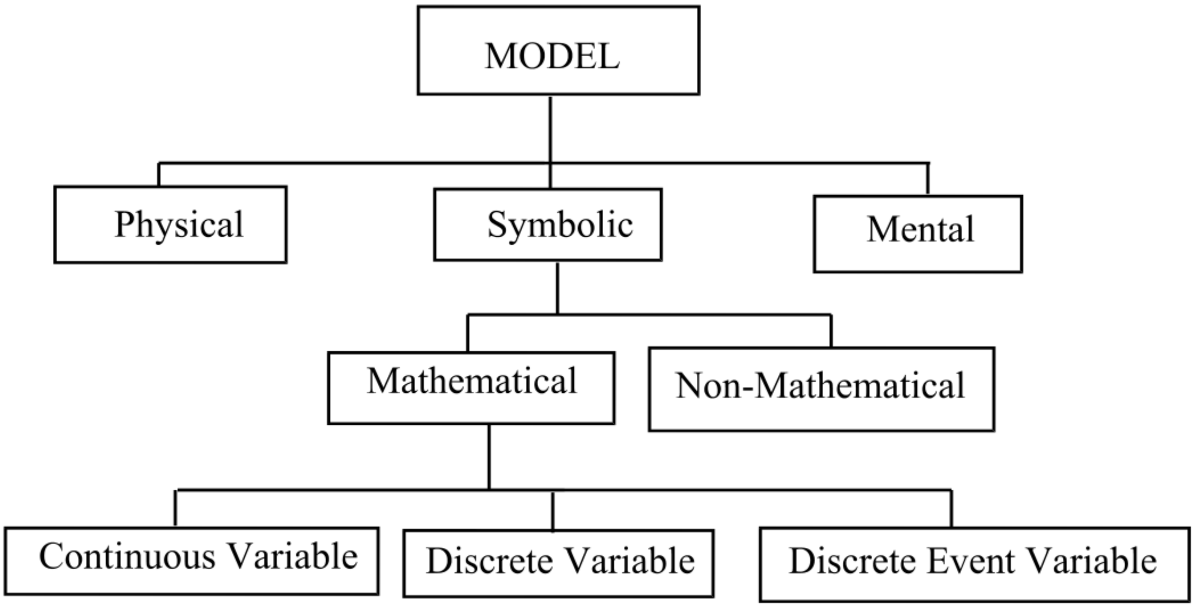


Figure 3 : Type of models, classic classification

Type of dynamic models:

- Continuos : ODE, DAE, PDE, Laplace Transformation
- Discrete: Difference equations, Z transform
- Discrete event : Markov, queue models, Petri Nets

A discrete system is one in which the state variable changes only at a discrete set of points in time (for example customers arriving each 2 minutes). They are characterized because state variables of the system change in a certain instant or instants sequence and stay constant for the rest of the time.

A continuous system is one in which the state variable changes continuously over time, for example the amount of water flow over a dam, the temperature's evolution in a room for any period of time or the evolution of liquid level in a tank.

A static simulation model, sometimes called Monte Carlo simulation, represents a system at particular point in time. Monte Carlo methods are especially useful for simulating phenomena with significant uncertainty in inputs and systems with many coupled degrees of freedom. Areas of application include Fluid dynamics, Physical chemistry, Computational physics, etc.

A dynamic simulation model represents systems as they change over time. An example of a dynamic model is the evolution of material in a stock that depends on the entrance and exit flows.

A deterministic simulation contains no random variables, in the other hand, a stochastic simulation involves one or more random variables as input. In a stochastic model, randomness is present, and state variables are not described by unique values, but rather by probability distributions.

From the information above the conveyor line problem can be modeled as a dynamic discrete system. This type of model is called DES (discrete event simulation). It is a method used to model real world systems that can be decomposed into a set of logically separate processes that autonomously progress through time. Each event occurs on a specific process and is assigned a logical time. The result of this event can be an outcome passed to one or more to other processes. The underlying statistical paradigm that supports DES is based on queuing theory (explained in the next paragraph).

Discrete event models are dynamic, stochastic, and discrete models where the state variables change its value in non-periodic instants of time. These instants of time correspond with the occurrence of an event. So, an event is defined as the instantaneous action that can change the state of the model.

Discrete event models are used in transportation, manufacturing, Logistics and supply chain, healthcare, etc.…

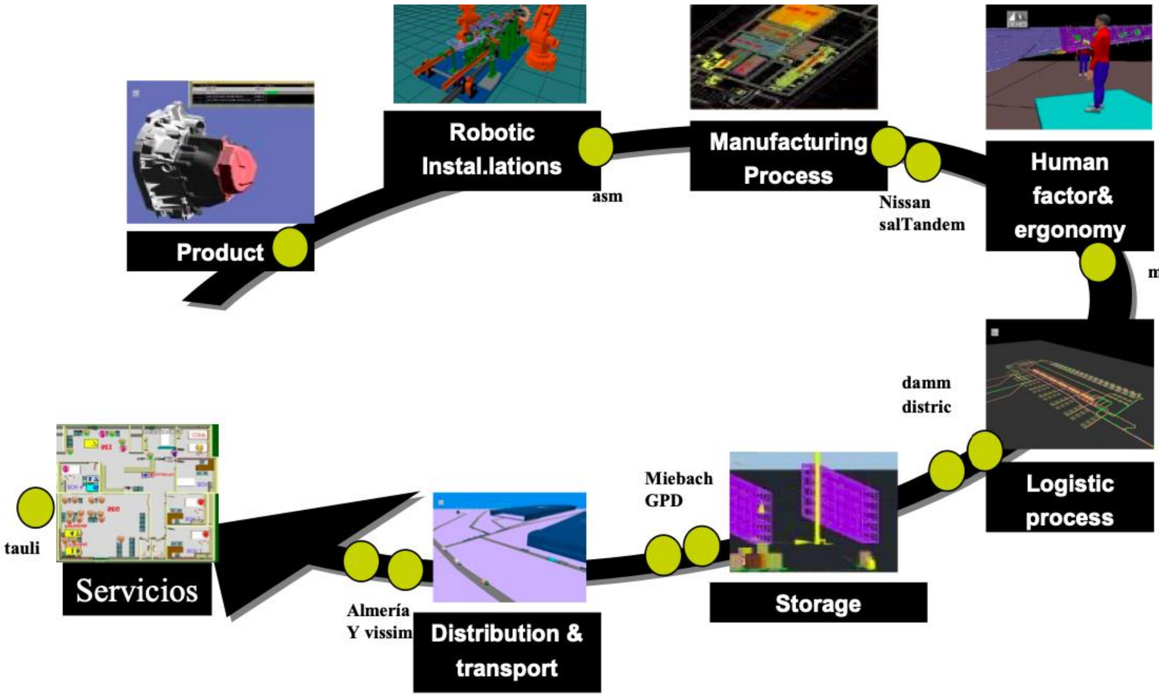


Figure 4 : discret event simulation application areas

6) QUEUE THEORY :

Queuing theory is the mathematical study of waiting lines, or queues. It is considered a branch of operations research because the results are often used when making business decisions about the resources needed to provide a service. Queuing theory had its origins in research by "Agner Krarup Erlang" when he created models to describe the system of Copenhagen Telephone Exchange company, a danish company. The ideas have since been applied in telecommunication, or industrial Engineering for instance.

For our application, queuing theory in manufacturing process involves the study and simulation of models to predict the behavior of a manufacturing process which attempt to provide services for randomly arising demands in manufacturing workstation. By utilizing queue model, we can make decisions about the waiting line which lead to better productivity. We can also apply the results of queuing theory to show how cycle time is related to the utilization of machine. The performance of the queuing model will be determined as a guide to increase efficiency of each workstation and suggestions to increase the performance of each workstation.

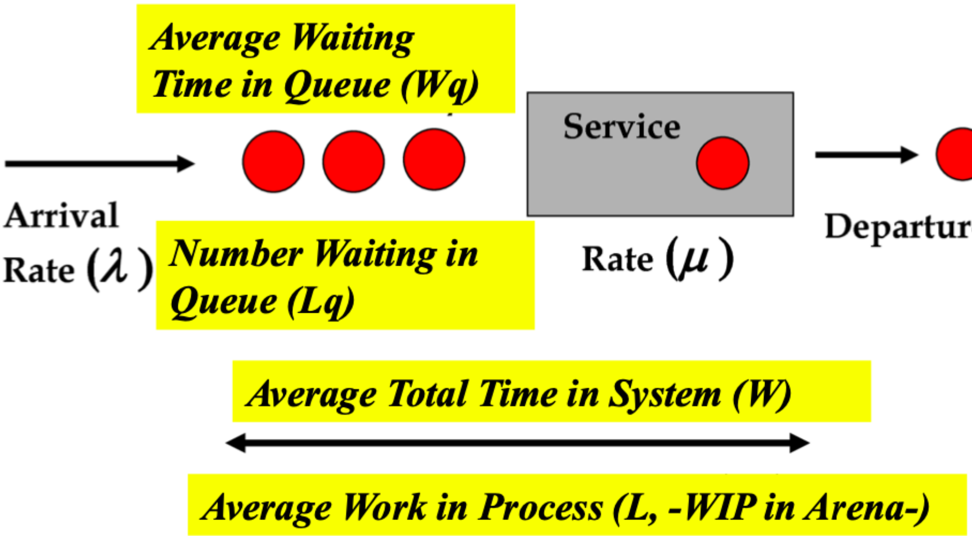


Figure 1 : Queue theory variables

- The entities can be people, work in process inventory, raw materials, incoming digital messages, or any other entities that can be modeled as lining up to wait for some process to take place.

- The arrival rate λ refers to the average number of entities who require service within a specific period of time.

- A queue is a set of entities waiting for a service. A capacitated queue is limited as to the number of entities who are allowed to wait in line. The queue discipline refers to the priority by which the next entity receive service is selected from a set of waiting entities. One common queue discipline is first-in-first-out, or FIFO.

- A server can be a human worker, a machine, or any other entity that can be modeled as executing some process for waiting entities.

- The service rate μ refers to the overall average number of entities a system can handle in a given time period.

- Utilization ρ refers to the proportion of time that a server (or system of servers) is busy handling entities.

The utilization factor, is also the probability that a server will be busy at any point in time:

$$\rho = \frac{\lambda}{S\mu}$$

Figure 2: Theoretical utilization formula

S represents the number of servers.

A simple example of queueing theory is a waiting queue in a restaurant. A goal of using queue theory for restaurant analysis is to improve customer wait times. This might be accomplished by adding more servers at certain times of the day, on busier days or after special events taking place in the area. Moreover, people feel more anxious if they don't know how long they must wait. The queuing theory can provide data on the waiting time, that can be communicated to the customer.

Another example is a waiting line to access a banking ATM system. Queue theory helps computing the utilization and the average total number of clients of the ATM system with one or many ATM machines and choose the best option. The average queue size could also be calculated to know if the bank has enough capacity to welcome all the customers.

For this project, it is important to describe the features of the queues that will be generated in the conveyor line, like the average wait time, and provides the tools for optimizing them. That is why the model of this project will be based on the Queuing theory to compute data concerning the conveying line.

7) LIFE CYCLE OF A SIMULATION PROJECT:

A simulation project is dynamic by nature. It is required a set of phases to successfully complete it. However, it is not a sequential process, it is possible that it would be necessary to modify a simulation phase after testing the model:

- Formulation of the problem: identification of the objectives of the simulation project, and formalization so that they are precise and measurable.

- Design of the conceptual model: Specification of the results or statistics that we hope to obtain from the simulation model to respond to the questions asked in the definition of objectives.

- Data collection: Obtaining all necessary data to reliably reproduce the real system in simulation.

- Construction of the model: Proceeding to build the model. Often, the effort concentrates more in the construction of the model than the resolution of the problem. That's the reason it is recommended to first build one or several simplified models that characterize the most essential parts of the system.

- Verification and validation: Checking the internal consistency between the model and real system.

- Experimentation and analysis: Analysis of data obtained from the simulation results, with the aim of understanding the behavior of the system to provide solutions to the initial problem.

- Documentation: To inform about the whole project and facilitate the reusability of the model in cases in which a possible interest in its future use is anticipated.

- Implementation: Which is taking decisions on the real system based on the results and analysis of the model.

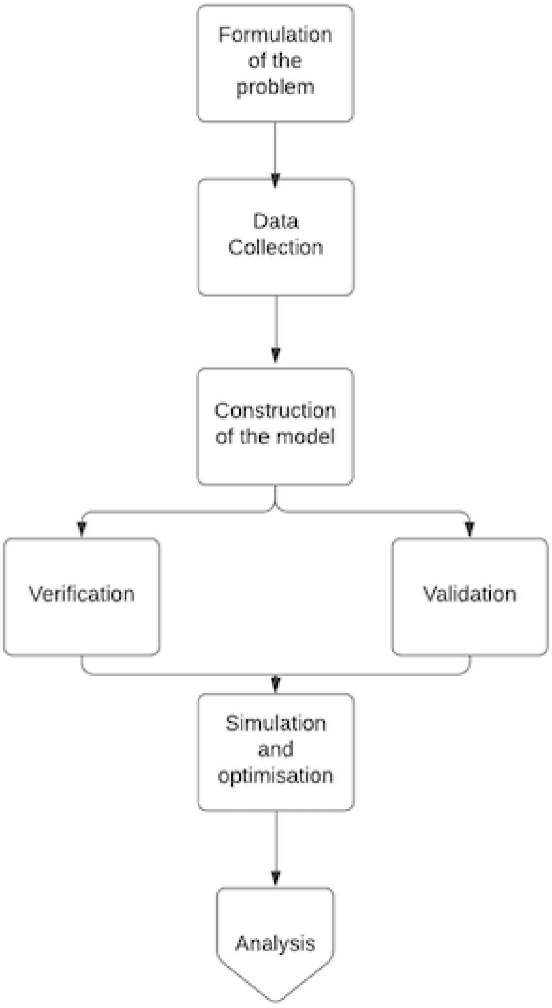


Figure 3 : Simulation Project life cycle

Another way to express the life cycle of a simulation project is in term of phases.

The first phase consists of the manufacturing system analysis. It is the phase when the system is defined, and the model is build using data.

The second phase, manufacturing system simulation, is the phase where the simulation results are analyzed to express conclusions on the system.

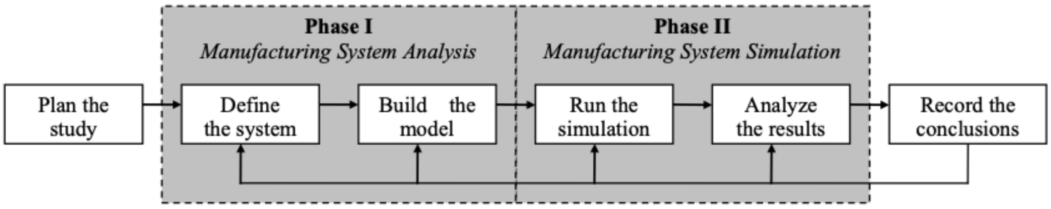


Figure 4: Simulation project life cycle in term of phases

In the rest of the report, the phases 1 and 2 will be referred to regarding our project.

8) PHASE I: MANUFACTURING SYSTEM ANALYSIS:

The first step of the simulation project is to define the system and plan the study. For this matter, a study case of the lab cell is defined as the following:

3 types of Parts (1, 2, and 3) must go through the production line to be manufactured. The manufacturing processes needed are process A and process B. Thus, at the entrance of the line, three parts can arrive, and at the end of the process, each part went through the needed process:

	Time in Process (in minutes)	
Parts	**Process A**	**Process B**
1	2	3
2	2	-
3	-	3

In the line, the parts move along the conveyor belts. Each one has bifurcations along its path:

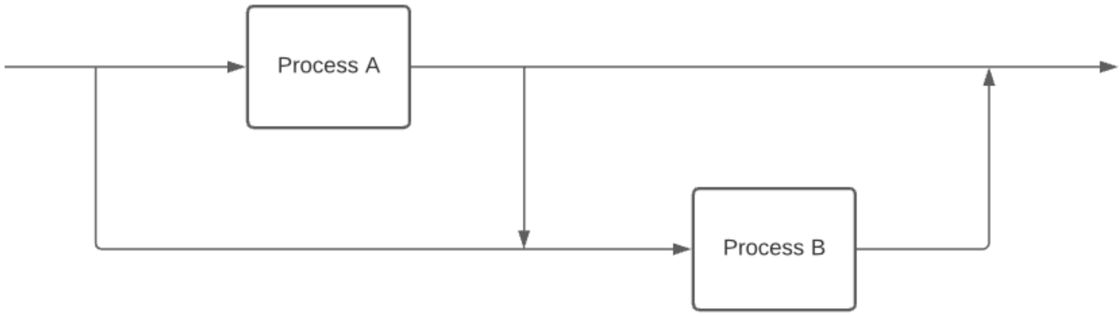


Figure 5 : Movement of parts along the conveyors diagram

At the first intersection, parts 1 and 2 continue their path while part 3 takes the first bifurcation. After parts 1 and 2 have been processed in Process A, part 1 rejoin part 3 alongside the second conveyor through the second bifurcation to be processed in B, while part 2 continue its paths. At the end, the rejoin the primary conveyor to be disposed.

Each bifurcation allows the parts to reach the work area where the relevant operation is carried out so that the part can advance in the process.

The following chart represent the percentage of arrival of each part 1, 2, and 3 depending on the arrival rate:

Parts	Percentage of arrival depending on the arrival rate
1	20%
2	40%
3	40%

The objective is to model this problem in ARENA and study the line. For this case study, use is made only of the Profibus line of the laboratory:

Figure 6: Overview of the laboratory facility

Each part moves through the system on metallic plates called trays. There are 16 stoppers in the Profibus line. Their role is to allow or block the passage of the trays, and they are activated by pneumatic solenoid valves. The following figure represent the schematic the top view of the lab line, with the blue square representing the Profibus part of the cell :

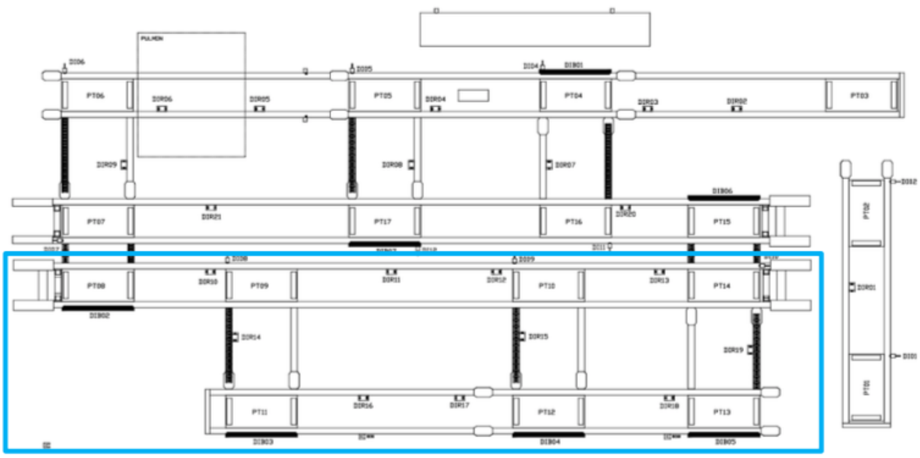


Figure 7: Illustration of the Profibus line

Moreover, there are also platforms on the Profibus line. Their function, like the stoppers, is to retain the parts. These platforms have two pneumatic cylinders: one that raises the platform and

another to that lowers it, which permits of blocking or permitting the passage of the trays. Each of these cylinders is managed by a pneumatic solenoid valve.

Finally, the Profibus line has four asynchronous motors for the conveyor belt. They are connected directly by a control contactor.

The process has different stoppers with two bifurcations. Within these stoppers are the two processes A and B. The stoppers are located in the positions 1 to 17 (figure 12).

- ***Construction of the simulation model:***

From the description of the process used in the project, we can understand that there are several parameters for the simulation.

First, there is a movement priority that needs to be defined regarding the different parts to be processed. In the real system, the parts can wait in stoppers (see image below):

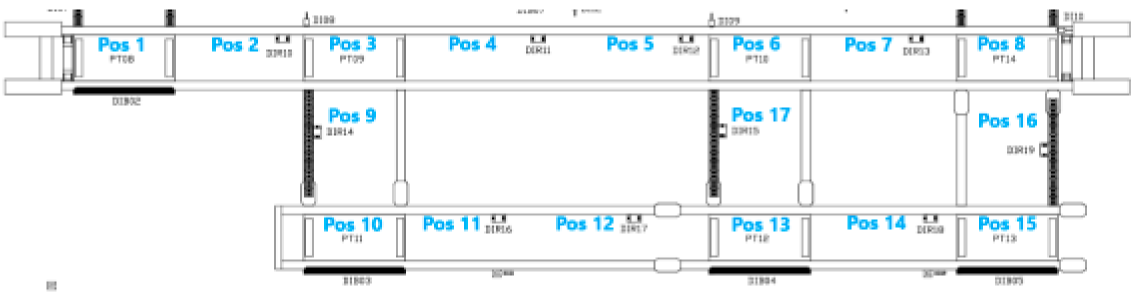


Figure 8 : Position of the stoppers in the line

The characteristic of these stoppers is that they allow the parts to wait if another one is in process. The characteristic of the stoppers is that their queue should only contain one part. There is a management of the priority in the process line that needs to be respected so that the model reflects reality.

Priority management is carried out by comparing the size of the queue generated. For example, a part can't access a process if there is a part already in process. Another example is the management of stoppers, a part can access the next stopper only if the queue of the former stopper is greater that the queue of the next one.

Another parameter considered is the FIFO (first in first out): the first part that arrives in the queue is the first to access the station.

In the following paragraph will be discussed the two models built. The first model used the conveying blocks of ARENA software, but this simulation was difficult to obtain. That is the reason that a second approach was done to simulate the project.

- ***First approach: using the conveying blocks in ARENA:***

To model the cell, the first approach was to use ARENA advanced transfer blocks. They are specific modules which allows to model a conveyor belt. By filling the data on the length of each conveyor, and their speed. An accurate representation of the system can be modeled. The problem with this approach is that it is difficult to respect the characteristics of the stoppers and to model them:

- FIFO: It is impossible to define the queue discipline.
- Queue priority management: It is impossible to define stations or positions on the conveyors belts model to simulate the behavior of a stopper. Specially defining the queue condition to release a part from a stopper.

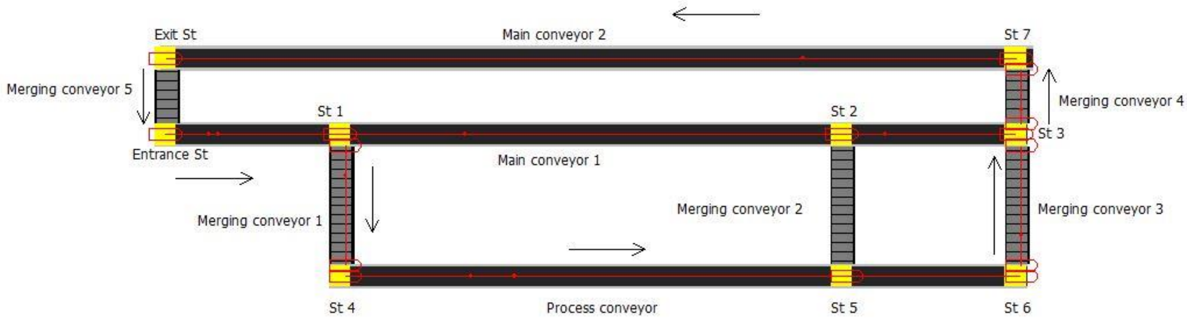


Figure 9 : First approach model

The second problem regarding this approach is the difficulty to analyze the simulation reports. Indeed, using the merging, convey, station, and segment blocks prevent us from having access to data regarding the simulation. For instance, the simulation report doesn't contain the number of elements in queue, or the utilization of resources.

- ***First approach: using delay blocks to model conveyors:***

At this point, a global vision of our system must be obtained. Instead of modelling conveyors by using advanced transfer ARENA blocks, the conveying process is modeled by calculating the time needed to move a part between each stopper. Data has been recorded in the lab to compute those values:

Stoppers	time (s)
1-2	4
2-3	3
3-10	7
10-12	5
13-15	4

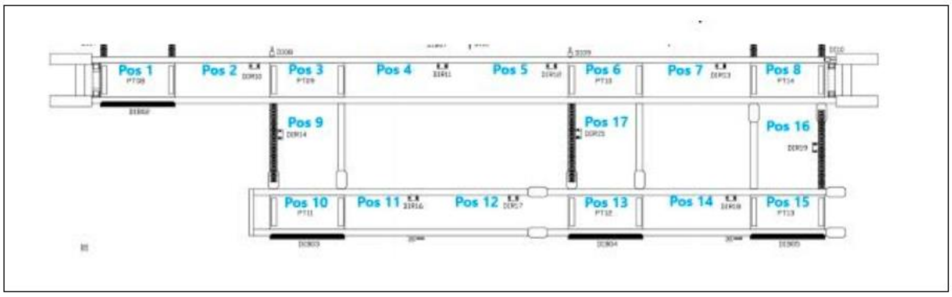


Figure 10 : Delay data record

The following figure illustrates the complete process in which the simulation is based. The details of each block are explained later on :

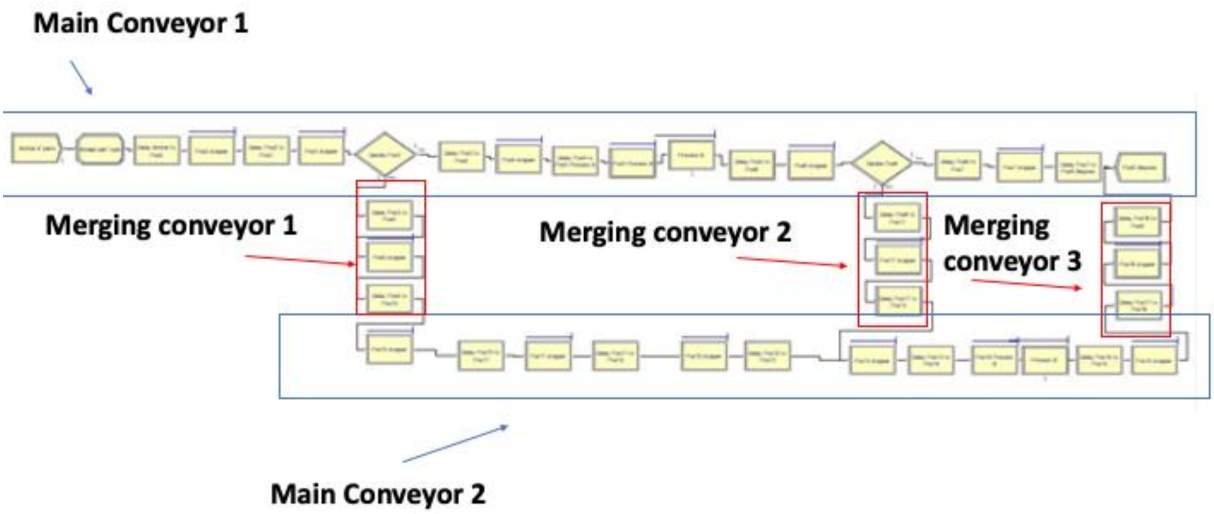


Figure 11 : ARENA MODEL

In ARENA the entities "parts" have been added:

Entity - Basic Process

	Entity Type	Initial Picture	Holding Cost / Hour	Initial VA Cost	Initial NVA Cost	Initial Waiting Cost	Initial Tran Cost	Initial Other Cost	Report Statistics
1	Parts	Picture.Report	0.0	0.0	0.0	0.0	0.0	0.0	☑

Figure 12: Entities in ARENA

For this chart the columns that we fill is the "Entity Type". The other columns are left by default.

The resources are the process A and B:

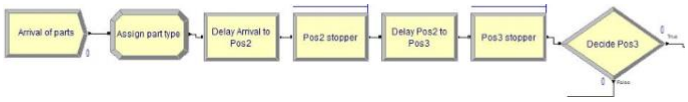
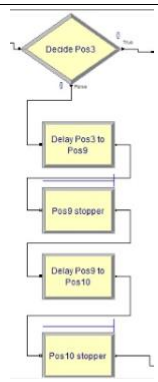
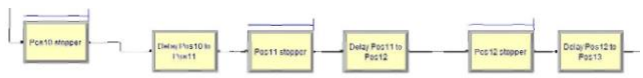
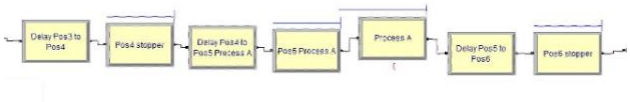
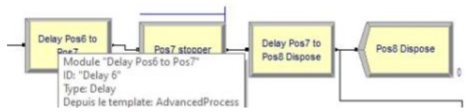
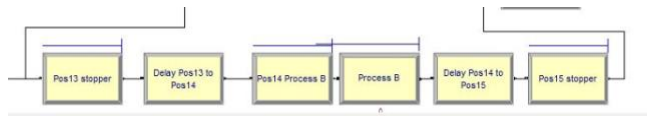
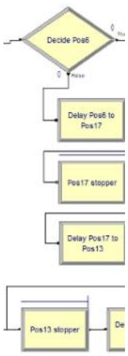
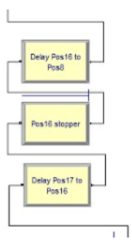
Resource - Basic Process

	Name	Type	Capacity	Busy / Hour	Idle / Hour	Per Use	StateSet Name	Failures	Report Statistics
1	Resource A	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
2	Resource B	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑

Figure 13: Ressources in ARENA

For this chart the columns that we fill is the "Entity Type", the "type", and the capacity. The other columns are left by default.

The following chart gives details on the position and the blocks used for each area:

Zone of the model	Position	Description
	Main conveyor 1	Arrival of parts -> assigning part type -> Delay -> stopper Pos2 -> Delay -> stopper Pos3->Delay Pos3 -> Intersection
	Merging conveyor 1	Intersection -> Delay -> stopper Pos9 -> Delay -> stopper Pos10
	Main conveyor 2	Stopper Pos10 -> Delay -> stopper Pos11 -> Delay -> stopper Pos12->Delay
	Main conveyor 1	Delay -> Stopper Pos4 -> Delay -> stopper Pos5 -> Process A -> Delay -> stopper Pos6
	Main conveyor 1	Delay -> Stopper Pos7 -> Delay -> pos8 dispose
	Main conveyor 2	stopper Pos13 -> Delay -> Stopper Pos14 -> Process B -> Delay -> stopper Pos15
	Merging conveyor 2	Intersection -> Delay -> stopper Pos17 -> Delay -> stopper Pos13
	Merging conveyor 3	Delay -> stopper Pos16 -> Delay

From the overall view of the process, the different components (modules) that make up the process and their configuration are analyzed:

a. Arrival of parts:

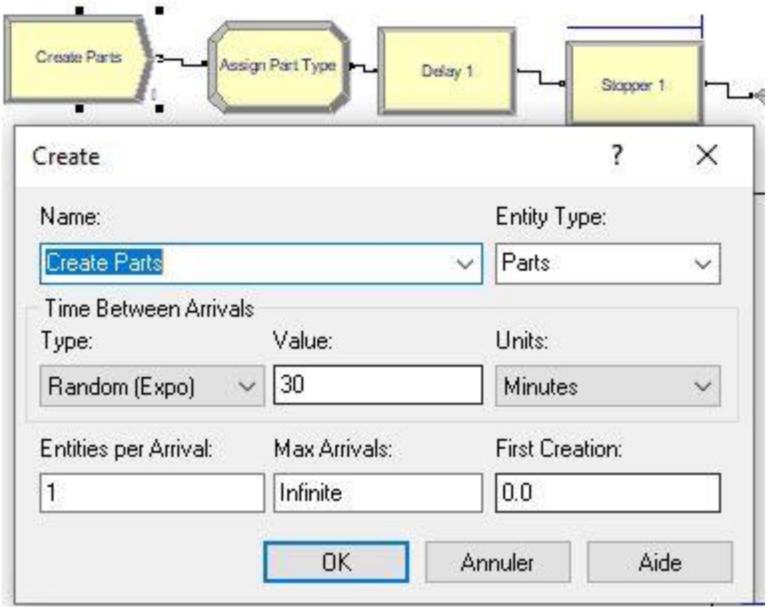


Figure 14 : arrival of parts in ARENA

The create module called "create parts" simulates the arrival of parts (entity type = parts). We have chosen for a first simulation a time between of arrivals of random exponential of 30 minutes.

b. Assigning parts type:

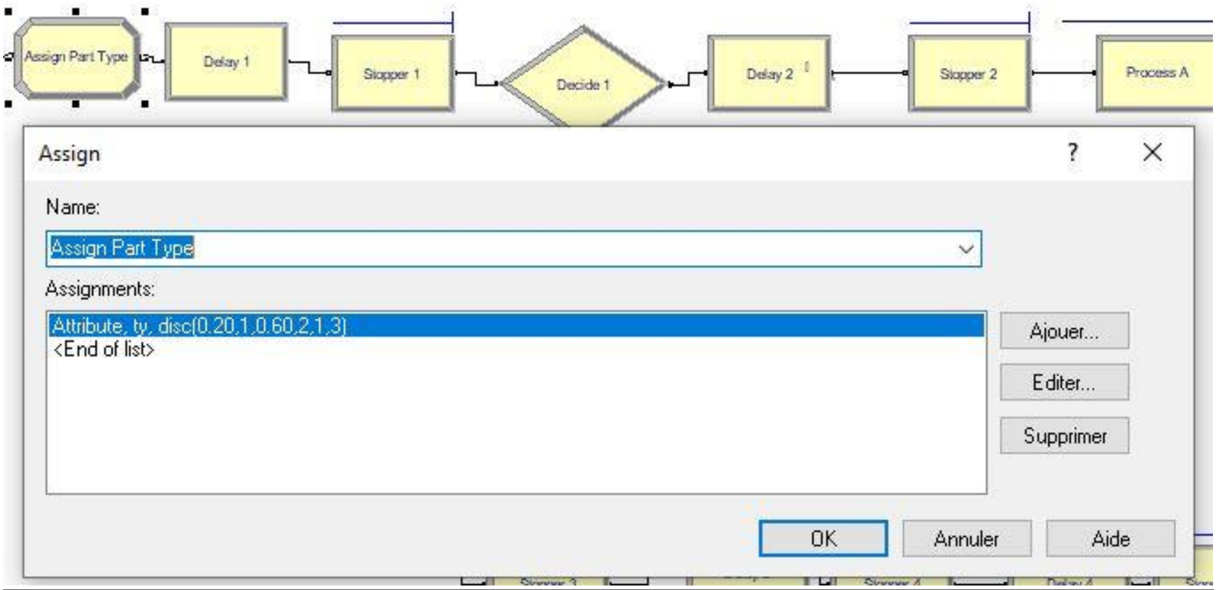


Figure 15: Assign block in ARENA

This block allows to assign a distribution on the percentage of arrival of the pieces depending on their type (1,2 or 3), as follows:

Parts	Percentage of arrival depending on the arrival rate
1	20%
2	40%
3	40%

c. Delays:

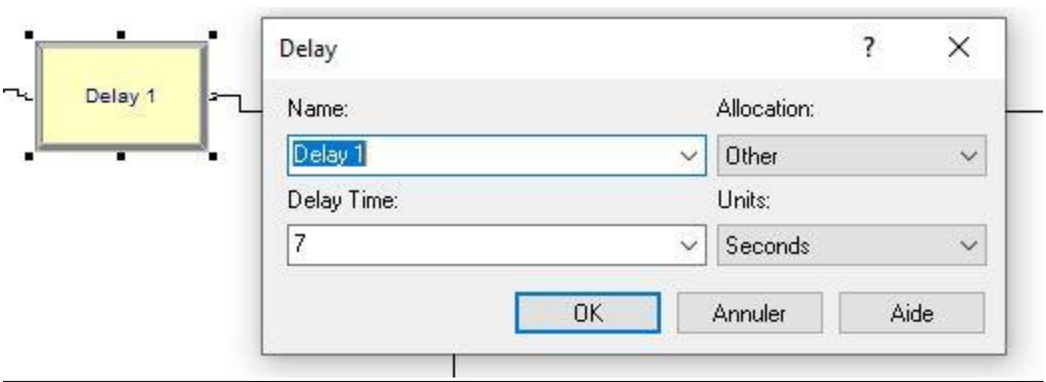


Figure 16: Delay block on ARENA

Throughout the process there are several blocks of type Delay. In these blocks, we add to the parts the time in which they are moving through the process.

Depending on the path they take, they encounter some delay blocks, which add to the parts the time they are moving through the process. Each section of the process has its own delays. These travel times have been timed in the laboratory like showed in figure 12.

This table shows the value of each Delay block:

Name	Delay time in seconds
Delay Arrival to Pos2	3
Delay Pos2 to Pos3	3
Delay Pos3 to Pos4	3
Delay Pos4 to Pos5	4
Delay Pos5 to Pos6	3
Delay Pos6 to Pos7	3
Delay Pos7 to Pos8 Dispose	3
Delay Pos3 to Pos9	2
Delay Pos9 to Pos10	4
Delay Pos10 to Pos11	2
Delay Pos11 to Pos12	4
Delay Pos12 to Pos13	3
Delay Pos6 to Pos17	2
Delay Pos17 to Pos13	4
Delay Pos13 to Pos14	3
Delay Pos14 to Pos15	3
Delay Pos16 to Pos8	2
Delay Pos17 to Pos16	4

d. <u>Stoppers :</u>

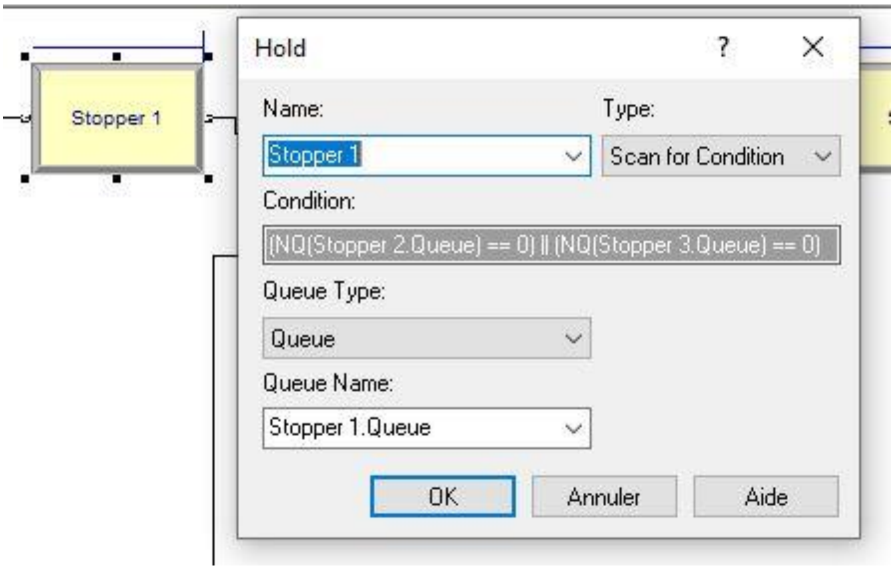


Figure 17: Hold block in ARENA

The stoppers are modeled with the "hold" block. This block simulates the behavior of a stopper in the manufacturing line, it means that it holds the movement of a part waiting for a process for instance. The characteristic of the stoppers is that the queue can only have 1 maximum element in the queue.

Moreover, the release of the part in the stopper is done with a condition, which makes the management of the queues and the priorities. In the following chart is explained the different queue conditions used for each stopper:

Name	Condition
Pos2 stopper	(Number in queue stopper 3= 0)
Pos3 stopper	(Number in queue stopper 4= 0) or (Number in queue stopper 9= 0)
Pos4 stopper	(Number in queue stopper 5 process A= 0)
Pos5 stopper Process A	Work in progress process A = 0
Pos6 stopper	(Number in queue stopper 7= 0) or (Number in queue stopper 17= 0)
Pos7 stopper	(Number in queue stopper 16= 0)
Pos9 stopper	(Number in queue stopper 10= 0)
Pos10 stopper	(Number in queue stopper 11= 0)
Pos11 stopper	(Number in queue stopper 12= 0)
Pos12 stopper	(Number in queue stopper 13= 0)
Pos17 stopper	(Number in queue stopper 13= 0)
Pos14 stopper process B	Work in progress process B = 0
Pos15 stopper	(Number in queue stopper 16= 0)
Pos16 stopper	(Number in queue stopper 7= 0)
Pos13 stopper	(Number in queue stopper 14= 0)

In brief, the following chart gives the list of all the queue of the model and the fact that they are following the FIFO principle:

Queue - Basic Process

	Name	Type	Shared	Report Statistics
1	Process A.Queue	First In First Out	☐	☑
2	Process B.Queue	First In First Out	☐	☑
3	Stopper 1.Queue	First In First Out	☐	☑
4	Stopper 2.Queue	First In First Out	☐	☑
5	Stopper 3.Queue	First In First Out	☐	☑
6	Stopper 4.Queue	First In First Out	☐	☑
7	Stopper 6.Queue	First In First Out	☐	☑
8	Stopper 5.Queue	First In First Out	☐	☑
9	Stopper 8.Queue	First In First Out	☐	☑
10	Stopper 7.Queue	First In First Out	☐	☑

Figure 18: List of the model queues

e. Decide blocks:

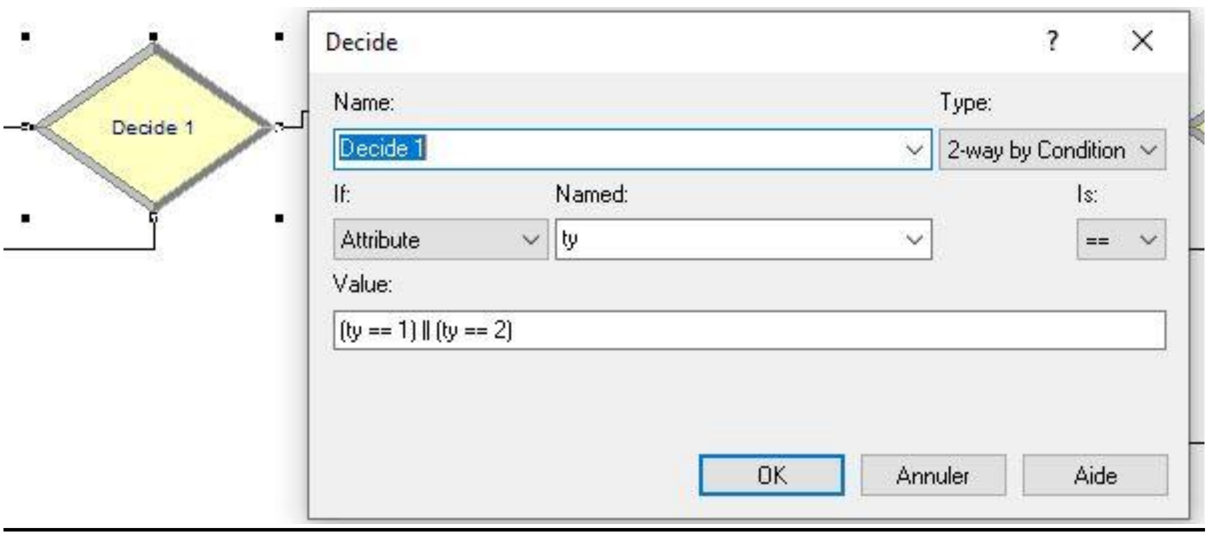


Figure 19: Decide block in ARENA

The decide blocks permits the movement of each part to the conveyors belt with the adequate process. There is two decide blocks in the ARENA model, and work with conditions depend on the value of the part: 1, 2 or 3.

f. Process A:

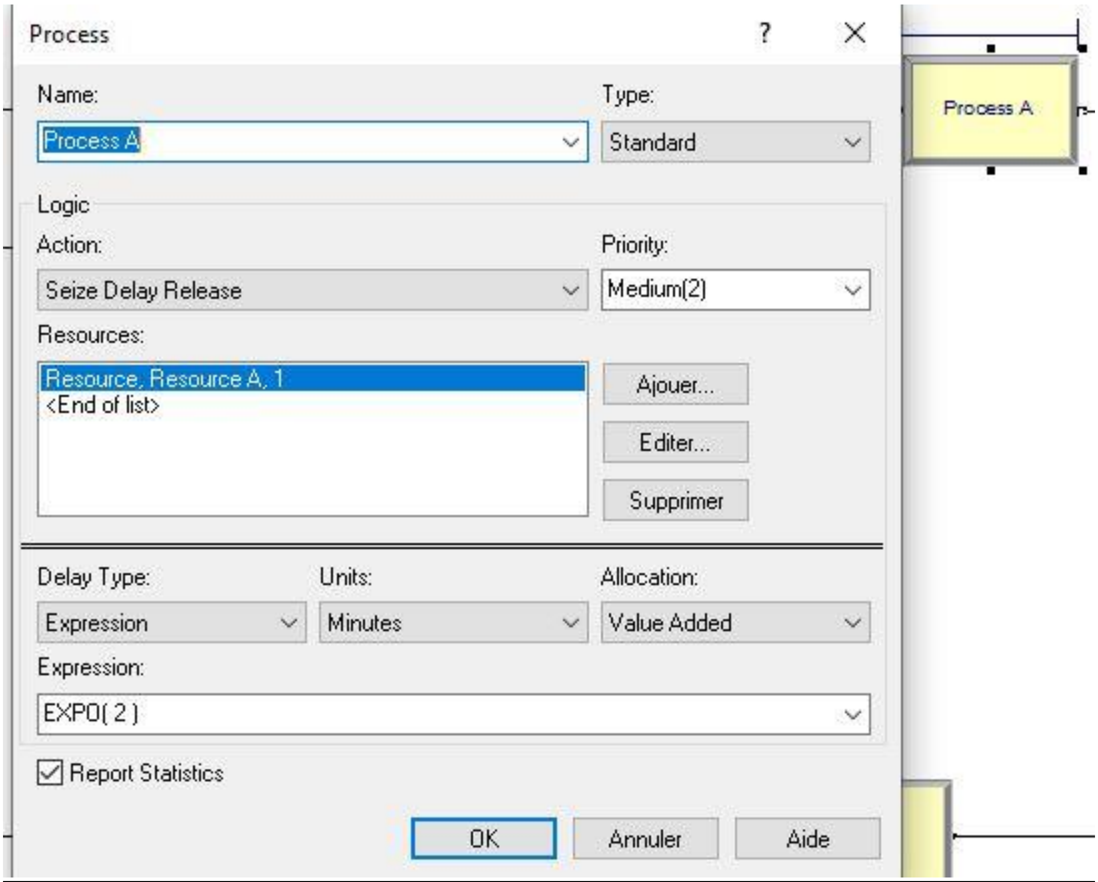


Figure 20: Process A block in ARENA

With this module of type process, we can simulate the process A. As can be seen in figure 19, a seize delay release resource is created with the name resource A. This operation has a fixed duration of exponential 2 minutes.

g. Process B:

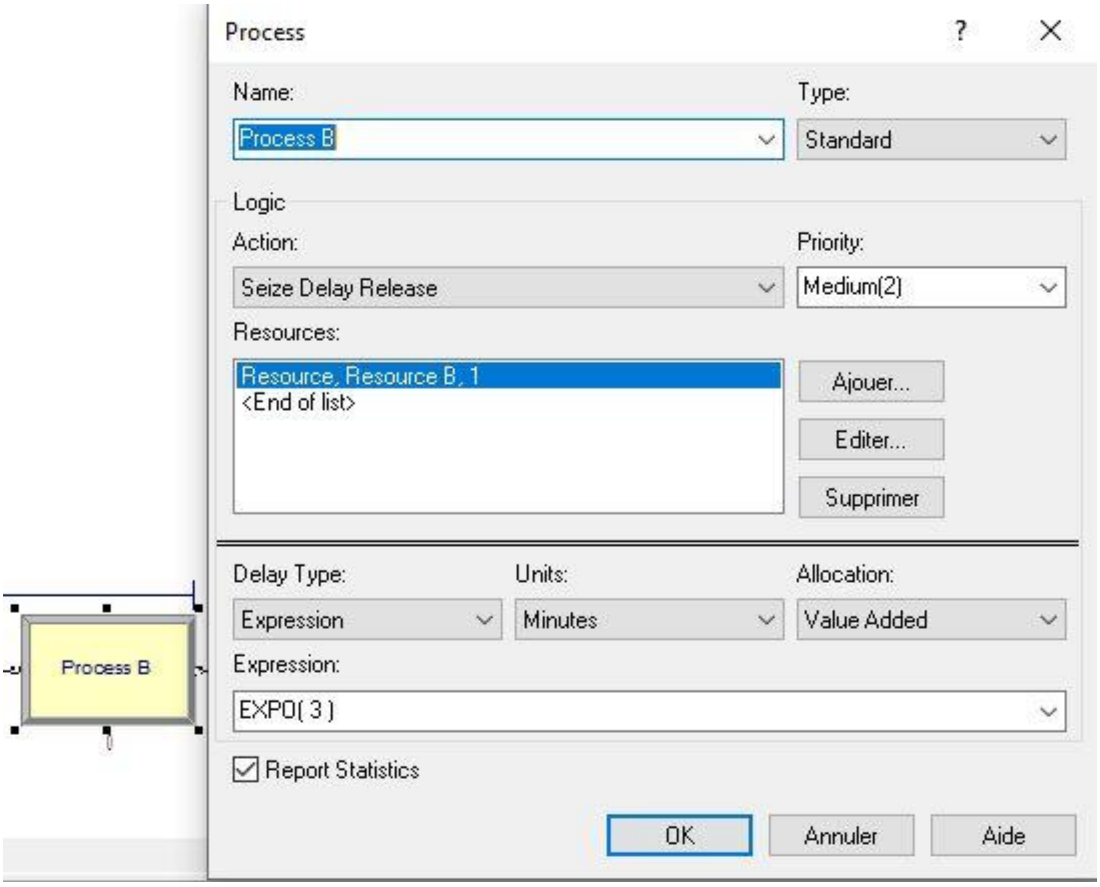


Figure 21: Process B block in ARENA

Here is the simulation of process B where resource B is seized delayed and released. This operation has a fixed duration of exponential 3 minutes.

h. Dispose:

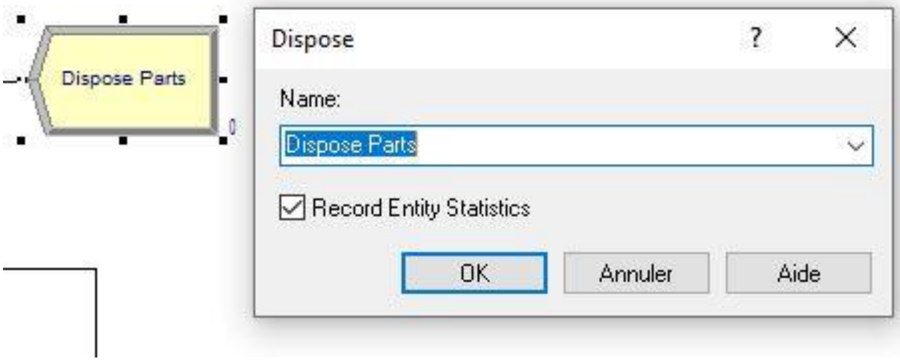


Figure 22 : Dispose block in ARENA

The output is represented by a dispose module. The block is located at the end of the simulation model, after the entities part 1, 2 and 3 have been processed and moved through the conveyor's belts.

9) PHASE II: MANUFACTURING SYSTEM SIMULATION:

The ARENA program offers the simulation data in a drop-down menu that can be downloaded in PDF format. Once the simulation is finished, the program asks the user to obtain the simulation results.

For the first simulation, the process is run for a working day (8h). Moreover, the simulation is run 10 times (10 replication), so have more accurate results.

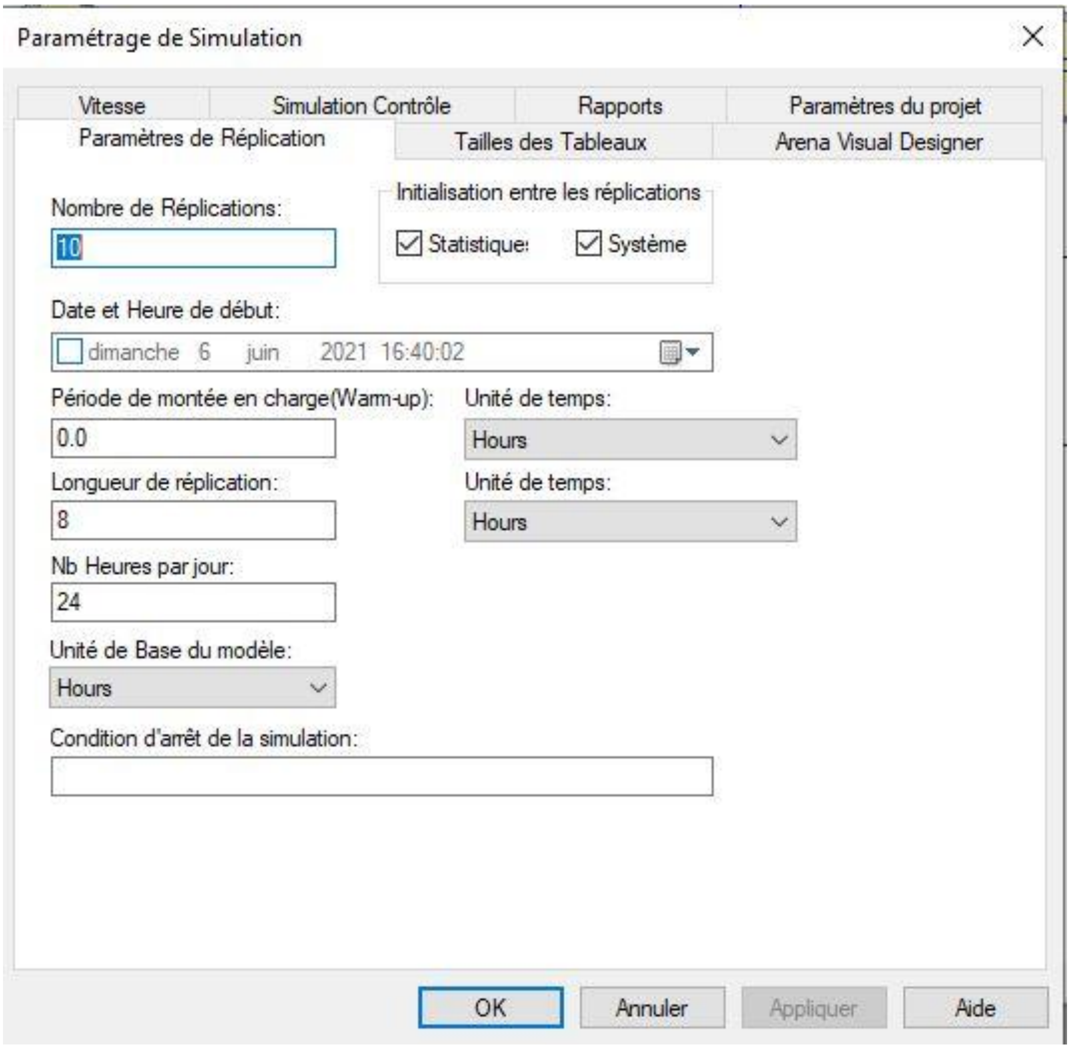


Figure 23: Running parameters in ARENA

The simulation results are displayed in the form of a drop-down menu in the same program. To download them, it is as simple as exporting the results in the desired format.

The following figure illustrates the general design of an ARENA simulation report. The actual simulation results are in the annexes:

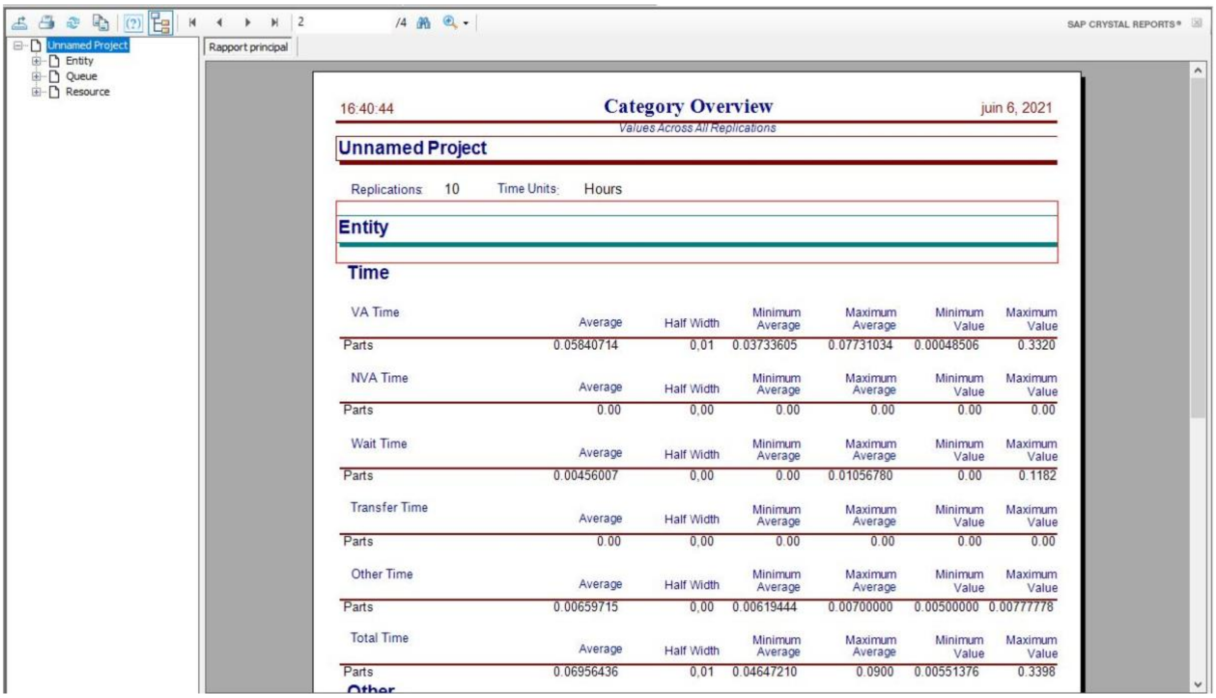


Figure 24: Simulation results report example in ARENA

- ***Simulation results:***

All the results of the following simulation are in the Annexes.

In this simulation, the arrival rate is equal to **5 minutes**. The duration is 8h, and the number of replications is 10 times (to have more accurate values):

<table>
<tr><th>Category Overview</th><th colspan="2">Type of DATA</th><th>Value</th></tr>
<tr><td>System</td><td colspan="2">Number out</td><td>96</td></tr>
<tr><td rowspan="4">Entity</td><td rowspan="3">Total time in System in min</td><td>Min</td><td>2,3</td></tr>
<tr><td>Max</td><td>15,6</td></tr>
<tr><td>Avg</td><td>4,5</td></tr>
<tr><td>Work in progress</td><td>Min</td><td>0</td></tr>
</table>

		Max	**6**
		Avg	**0,9118**
Queues	Maximum number of parts in queue	Pos2	**0**
		Pos3	**0**
		Pos4	**1**
		Pos5	**2**
		Pos6	**0**
		Pos7	**0**
		Pos9	**0**
		Pos10	**0**
		Pos11	**0**
		Pos12	**1**
		Pos13	**2**
		Pos14	**2**
		Pos15	**0**
		Pos16	**0**
		Pos17	**1**
		Process A	**0**
		Process B	**0**
Usage	Utilization	Ressource A	**23,7%**
		Ressource B	**39,3%**

With	Simulation time	**8h**
	Replications	**10**

- System: For the study case, in 8h the line produces 96 units.

- Entity: The average time spent by each part in the system is 4,5 minutes. With the longest time being 15,6 minutes, and the shortest being 2,3 minutes.

  Concerning the work in progress, it represents how many units are moving inside the line, the average being for the manufacturing line of 0,9 units, which is less than 1 unit. This result shows that in average there is an average of 1 unit moving through the system. This value is logical giving the fact that the arrival rate is greater than the time spent in the system. In brief, the model values are congruent with the study case.

- Queues: This value represents the maximum number of parts in each stopper. The role of the stoppers has already been discussed, and the characteristic being that they can only contain one part. This information means that the maximum value shouldn't exceed one. For this case, most of the stoppers have a value of 0, which shows that the system is working well. Some stoppers have a value of 1, which is a correct value. Finally, some stoppers have 2 as a value. This information means that the arrival rate might be high for the system to work correctly, but in any case, there is no blatant value (example: 53) that shows a flagrant error of the model. If the value of the arrival time is greater than 5 minutes, most of the stoppers have 0 as a queue or a maximum of 1, which reassures of the likely validity of the model. In brief, the computations of these parameters shows that the system behaves as expected, this shows also that the following queuing parameters for each stopper are adequate, and they can be implemented in the PLC of the real system as an improvement opportunity:

Name	Condition
Pos2 stopper	(Number in queue stopper 3= 0)
Pos3 stopper	(Number in queue stopper 4= 0) or (Number in queue stopper 9= 0)
Pos4 stopper	(Number in queue stopper 5 process A= 0)
Pos5 stopper Process A	Work in progress process A = 0
Pos6 stopper	(Number in queue stopper 7= 0) or (Number in queue stopper 17= 0)
Pos7 stopper	(Number in queue stopper 16= 0)
Pos9 stopper	(Number in queue stopper 10= 0)
Pos10 stopper	(Number in queue stopper 11= 0)
pos11 stopper	(Number in queue stopper 12= 0)
pos12 stopper	(Number in queue stopper 13= 0)
pos17 stopper	(Number in queue stopper 13= 0)
Pos14 stopper process B	Work in progress process B = 0
pos15 stopper	(Number in queue stopper 16= 0)
pos16 stopper	(Number in queue stopper 7= 0)
pos13 stopper	(Number in queue stopper 14= 0)

- Usage: The utilization of the resource B (39,3 %) is greater than the utilization of the resource A (23,7 %). This information is correct given the fact that the service time of the process B is longer. Moreover, the value doesn't exceed 100 %, which shows that the number of servers is adequate (the capacity of each process).

As a first approach, the results of the simulation are coherent with the model and its expected behavior. To verify the ARENA model, two different approaches are performed.

The first approach consists of comparing the ARENA model with the Queue Theory, and the second approach is experimental.

- ***Model verification:***

The first approach consists of comparing the ARENA model with the Queue Theory: The same ARENA model is simulated, except that the stoppers are deleted. The objective is to model the line with the queue theory principle. To validate our model, the values between queue theory and the model should be similar.

The following model represents the queue theory model, as explained, the stoppers are the deleted:

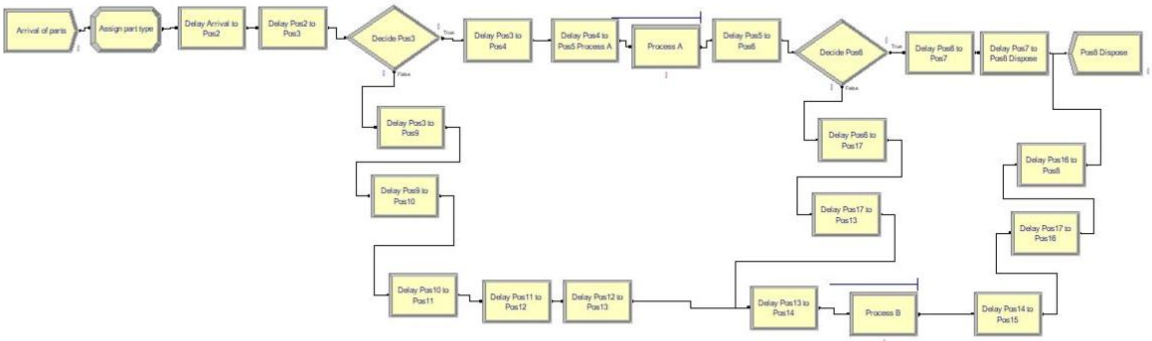


Figure 25 : Queue Theory Model

The following model represents the queue theory model, as explained, the stoppers are the deleted:

The following chart gives details on the position and the blocks used for each area:

Position	Description
Main conveyor 1	Arrival of parts -> assigning part type -> Delay -> Delay -> Delay Pos3 -> Intersection
Merging conveyor 1	Intersection -> Delay -> Delay ->
Main conveyor 2	-> Delay -> Delay -->Delay
Main conveyor 1	Delay -> Delay -> Process A -> Delay ->
Main conveyor 1	Delay -> Delay ->
Main conveyor 2	-> Delay -> Process B -> Delay ->
Merging conveyor 2	Intersection -> Delay -> Delay ->
Merging conveyor 3	Delay -> -> Delay

The following chart shows the value of important data regarding the model (output, total time, etc.), and compare the model and theoretical value by calculating the deviation:

Category Overview	Type of DATA		Model Value	Theoretical Value	Deviation
System	Number out		218,000	218	**0,00%**
Entity	Total time in system in minutes	Avg	29,206	29,5328	**1,11%**
	Work in progress	Avg	16,056	16,1187	**0,39%**
	Wait time in minutes	Avg	25,343	25,6969	**1,38%**
Queue	Maximum number of parts in queue	Process A	0,000	5	**100,00%**
		Process B	0,000	47	**100,00%**
	Waiting time in queue in minutes	Process A	0,000	9	**100,00%**
		Process B	0,000	115	**100,00%**
Usage	Utilization	Ressource A	60,66%	60,5%	**-0,33%**
		Ressource B	97,15%	97,2%	**0,00%**

With	Simulation time	**8h**
	Replications	**10**
	Arrival rate in minutes	**2**

The following chart gives details on the position and the blocks used for each area:

The deviation for the data set is less than **2%,** which proves the validity of the model regarding the queue theory. Moreover, there is difference in the queue located in Process A and B: with the stoppers (model value), the queue is equal to zero but without them (theoretical value), there is a big number of elements waiting in the queue for the process (value of deviation in red). It is found that the line has major bottlenecks if the stoppers don't have the queueing management conditions. This shows the role and the impact of the stoppers, proving that they are behaving as expected.

In Brief, the model is valid and respects the queue theory. We can use this model to find improvement opportunities for the manufacturing cell.

In this paragraph we will show how our model is valid using an experimental approach. The test vector chosen is a part going through the "main conveyor 1", from the stoppers 2, 3, 4,5,6, and 7, and getting processed in stopper 6 for 20 seconds.

Figure 26: Perfoming the test in the lab

The following diagram represents the test vector scheme:

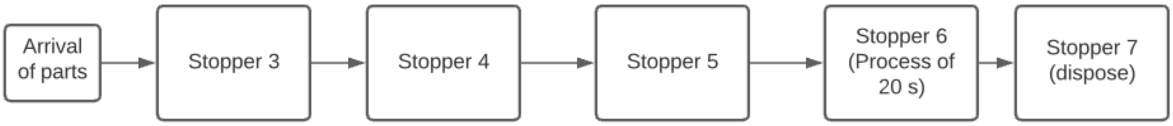


Figure 27: test vector scheme

The location of the process for the test in the manufacturing line is as proposed in the scheme below:

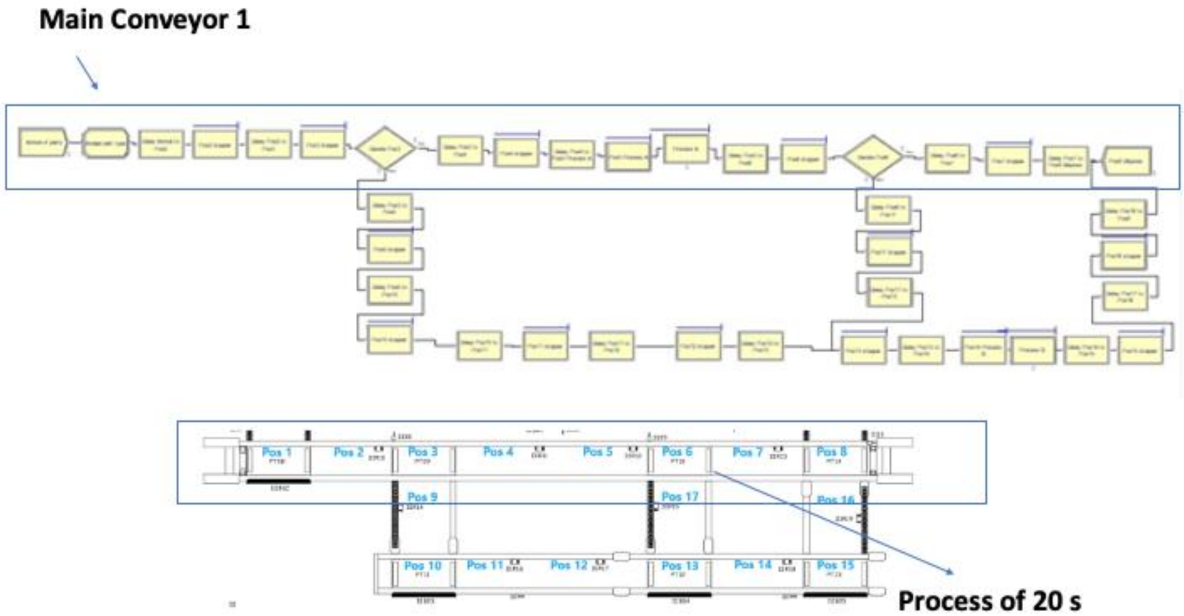


Figure 28: location of the process for the test vector

The following chart shows the value of important data regarding the model and the experimental test (total time in system, queues, etc.) and compare the model and experimental result by calculating the deviation:

Category Overview	Type of DATA		Model Value	Experimental value	Deviation
Entity	Total time in system in minutes	Avg	1,70	2,10	**19,05%**
Queue	Maximum number of parts in queue	Stopper 2	1,00	1,00	**0,00%**
		Stopper 3	1,00	1,00	**0,00%**
		Stopper 4	1,00	1,00	**0,00%**
		Stopper 5	1,00	1,00	**0,00%**
		Stopper 6	1,00	1,00	**0,00%**
	Waiting time in queue in minutes	Stopper 2	0,33	0,50	**34,00%**
		Stopper 3	0,33	0,40	**17,50%**
		Stopper 4	0,33	0,35	**5,71%**
		Stopper 5	0,33	0,35	**5,71%**
		Stopper 6	0,33	0,33	**0,00%**

AVG Deviation	**7,45%**

The average deviation for the data set is **7,45 %**. There is no deviation concerning the size of the queues, and the most deviation is located in the waiting time for some stoppers. The deviation is explained by the fact that the experimental test was recorded on a phone and the gathering of times was not precise.

- ***Improvement opportunities:***

The first improvement opportunity is to implement the Management of the Queue conditions on the PLC program of each stopper. The following logic diagram explains the scheme flow that the line should follow:

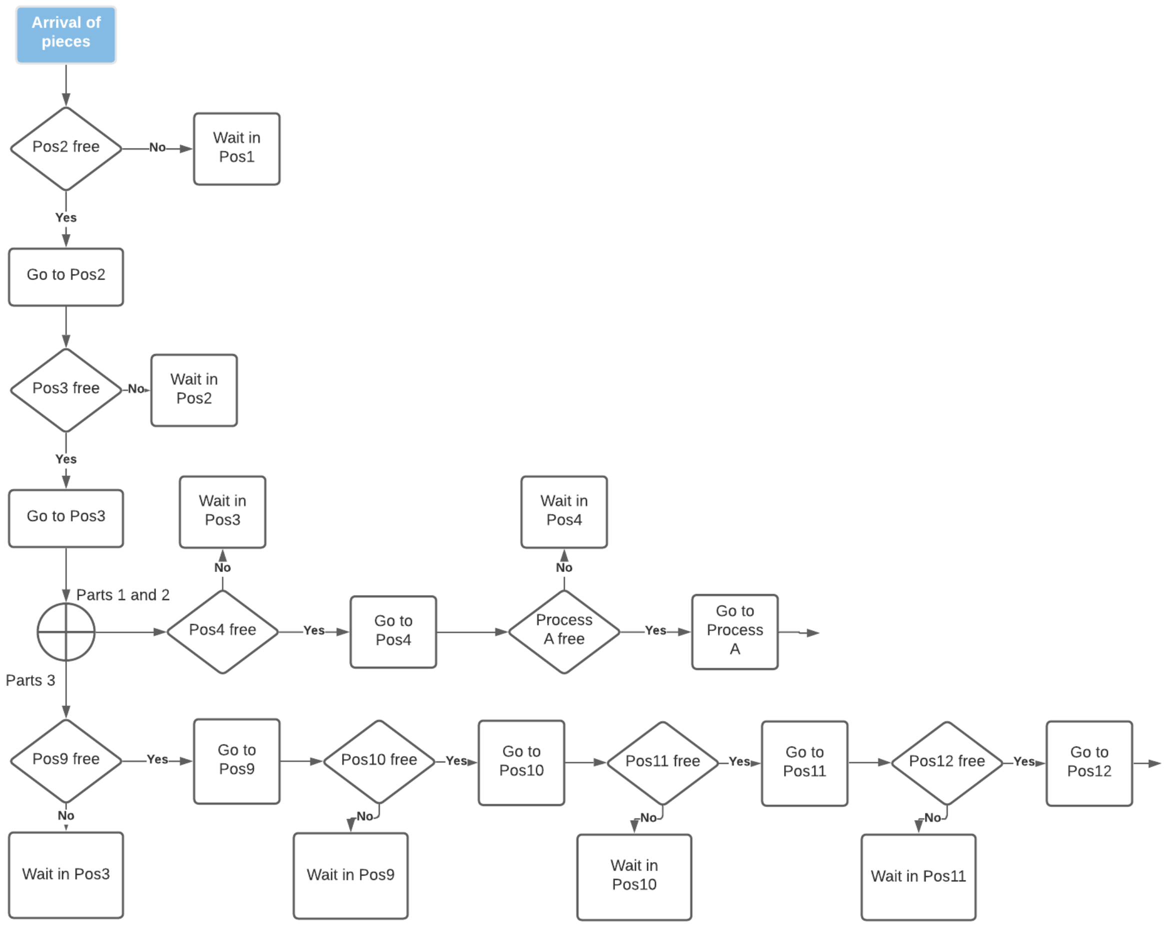


Figure 29: part 1 of the flow diagram

In this first part the flow of the part is modeled following the conditions of the stoppers. At the upper left part is the start of the line (arrival of parts).

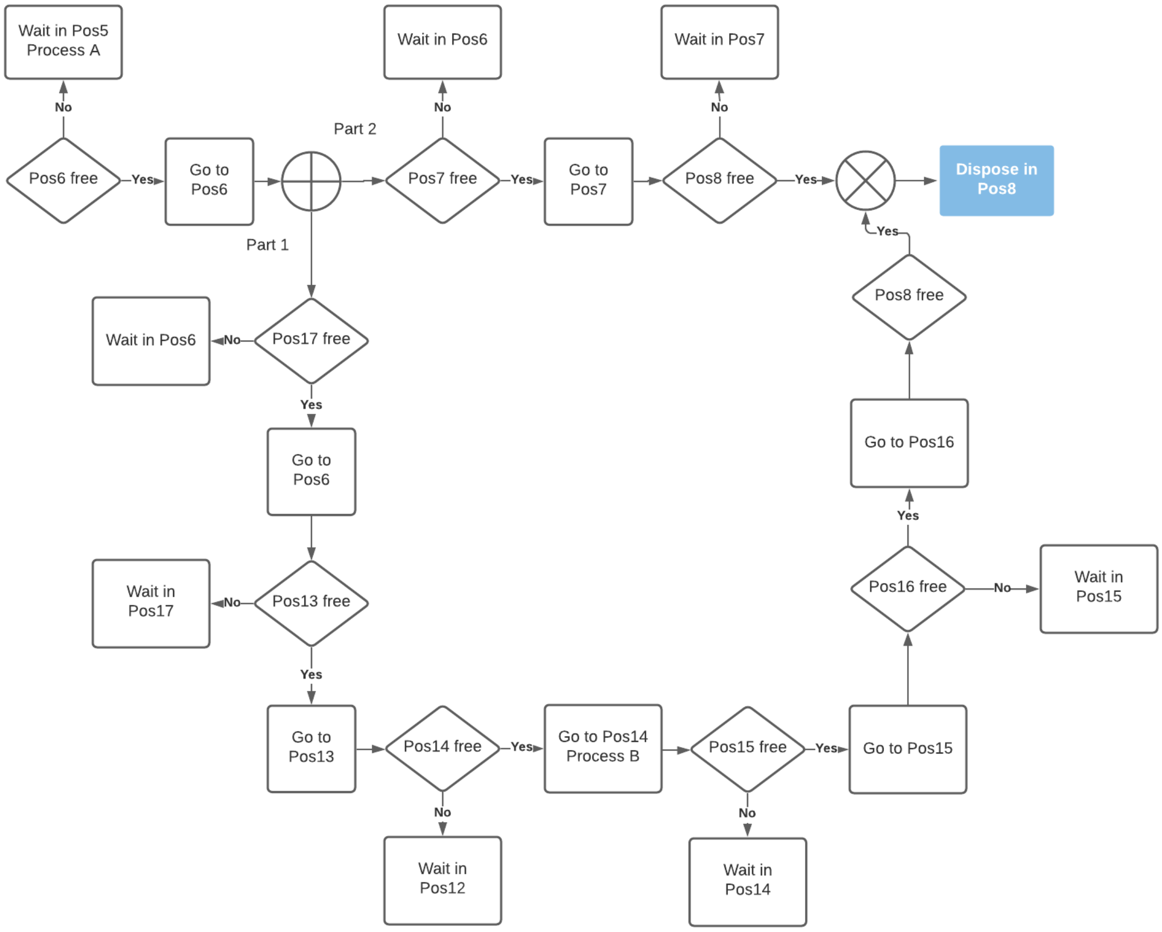


Figure 30: Part 2 of the flow diagram

The following conditions for each stopper (pos2 to 16) need to be implemented in the PLC program of the line, specifically in the code of the behavior of the stoppers:

Name	Condition
Pos2 stopper	(Number in queue stopper 3= 0)
Pos3 stopper	(Number in queue stopper 4= 0) or (Number in queue stopper 9= 0)
Pos4 stopper	(Number in queue stopper 5 process A= 0)
Pos5 stopper Process A	Work in progress process A = 0
Pos6 stopper	(Number in queue stopper 7= 0) or (Number in queue stopper 17= 0)
Pos7 stopper	(Number in queue stopper 16= 0)
Pos9 stopper	(Number in queue stopper 10= 0)
Pos10 stopper	(Number in queue stopper 11= 0)
pos11 stopper	(Number in queue stopper 12= 0)
pos12 stopper	(Number in queue stopper 13= 0)
pos17 stopper	(Number in queue stopper 13= 0)
Pos14 stopper process B	Work in progress process B = 0
pos15 stopper	(Number in queue stopper 16= 0)
pos16 stopper	(Number in queue stopper 7= 0)
pos13 stopper	(Number in queue stopper 14= 0)

10) CONCLUSION:

The goals of this project were achieved by measuring the performance of the TR2 lab production line. The following table summarizes the different milestones of the thesis and their achievement stage:

Scopes of the project	Achievement state	Details
Study and understanding of the available industrial line at school facilities	☑	Description of the line functioning: stoppers, plates, etc.
State of the art in industrial processes modelling and simulation	☑	Simulation types, queue theory, DES, etc
Selection and determination of parameters considered for the simulation of the process	☑	Phase 1 : Manufacturing System Analysis
Implementation of the simulation model based on Arena software	☑	Phase 1 : Manufacturing System Analysis
Definition of test vectors and validation of the model	☑	Phase 2: Manufacturing System Simulation Test 1 : comparing with Queue theory Test 2 : comparing with an experimental test
Identification of manufacturing line limitations and improvement opportunities	☑	Phase 2: Manufacturing System Simulation Implementation of Queue Management Conditons in stoppers to avoid bottlenecks
Documentation and presentation	☑	Report

This project proves the powerful effect of using the simulation in situations where it is too hard or even impossible to improve the performance of a manufacturing line when large number of variables and parameters are affecting the system.

On a personal level, it has been an enriching experience. I started with a beginner level in industrial process simulation and specially on ARENA software. As a result of the development of this paper I am now more efficient and skilled in simulating manufacturing lines, while keeping in mind to optimize the available resources to the maximum available.

To conclude, a possible continuation of the work would be using the ARENA model to modify physically the line (changing the number of stoppers, changing the direction of the conveyor belts, etc.) to improve the line capacity and daily output.

11) BUDGET:

There are two types of cost related to the completion of this project: Direct and Indirect.

The direct cost contains the hours needed for the completion of the model, which is approximated to 5 months of work (duration of the thesis), working 3 hours a day, on working days (5 days per week), which gives an approximation of 300 hours worked. The second hypothesis is that the phase 1: Manufacturing System Analysis took most of the time (80 %), and the rest is for realizing the simulation and interpreting the results.

The indirect costs are 10% of the direct costs.

Type of Cost	Phase of the project	Duration in h	Hourly rate (€/h)	Cost
Direct	Phase I : Manufacturing System Design	240	25	6 000,00 €
	Phase II : Manufacturing System Simulation	60		1 500,00 €
Indirect	10% of Direct costs	-	-	750,00 €

Total	**8 250,00 €**

12) BIBLIOGRAPHY:

- Simulation models:

  https://en.wikipedia.org/wiki/Simulation_in_manufacturing_systems

- Discrete event simulation:

  https://www.researchgate.net/publication/224209141_Discrete_event_simulation_class_for_engineering_graduate_students

- ARENA documentation:

  https://www.arenasimulation.com/what-is-simulation/discrete-event-simulation-software

- Queue theory:

  https://www0.gsb.columbia.edu/mygsb/faculty/research/pubfiles/5474/queueing%20theory%20and%20modeling.pdf

- Life cycle of a simulation project:

  https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1022&context=imsefacpub

13) ANNEXES

20:02:45 **Category Overview** juin 14, 2021

Values Across All Replications

Unnamed Project

Replications: 10 Time Units: Minutes

Key Performance Indicators

System	Average
Number Out	96

Model Filename: C:\Users\Mac de Mehdi\Desktop\Nouveau dossier\Final Model Page 1 of 4

Figure 31: Page 1/4 ARENA Report

20:02:45 **Category Overview** juin 14, 2021

Values Across All Replications

Unnamed Project

Replications: 10 Time Units: Minutes

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maxim Va
Parts	3.1178	0,07	2.9506	3.2404	2.0000	5.00

NVA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maxim Va
Parts	0.00	0,00	0.00	0.00	0.00	0.

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maxim Va
Parts	0.8972	0,17	0.6003	1.2874	0.00	10.09

Transfer Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maxim Va
Parts	0.00	0,00	0.00	0.00	0.00	0.

Other Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maxim Va
Parts	0.4894	0,01	0.4803	0.5051	0.3667	0.56

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maxim Va
Parts	4.5044	0,23	4.0407	4.9533	2.3667	15.66

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
Parts	97.0000	6,98	82.0000	115.00

Number Out	Average	Half Width	Minimum Average	Maximum Average
Parts	96.2000	6,97	81.0000	115.00

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maxim Va
Parts	0.9118	0,10	0.6845	1.1663	0.00	6.00

Model Filename: C:\Users\Mac de Mehdi\Desktop\Nouveau dossier\Final Model Page 2 of 4

Figure 32: Page 2/4 ARENA report

20:02:45 **Category Overview** juin 14, 2021

Values Across All Replications

Unnamed Project

Replications: 10 Time Units: Minutes

Queue

Time

Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maxim Va
Pos10 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos11 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos12 stopper.Queue	0.01910610	0,02	0.00	0.08402996	0.00	2.85
Pos13 stopper.Queue	0.1468	0,08	0.01684269	0.3534	0.00	5.93
Pos14 Process B.Queue	0.9279	0,17	0.6863	1.3723	0.00	5.95
Pos15 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos16 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos17 stopper.Queue	0.02308819	0,03	0.00	0.1229	0.00	2.34
Pos2 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos3 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos4 stopper.Queue	0.01152092	0,01	0.00	0.05354191	0.00	1.16
Pos5 Process A.Queue	0.2871	0,08	0.1390	0.5251	0.00	3.74
Pos6 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos7 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos9 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Process A.Queue	0.00	0,00	0.00	0.00	0.00	0.
Process B.Queue	0.00	0,00	0.00	0.00	0.00	0.

Other

Number Waiting	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maxim Va
Pos10 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos11 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos12 stopper.Queue	0.00153627	0,00	0.00	0.00595212	0.00	1.00
Pos13 stopper.Queue	0.02038633	0,01	0.00207025	0.04520445	0.00	2.00
Pos14 Process B.Queue	0.1243	0,03	0.07005687	0.1876	0.00	2.00
Pos15 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos16 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos17 stopper.Queue	0.00129998	0,00	0.00	0.00691070	0.00	1.00
Pos2 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos3 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos4 stopper.Queue	0.00139521	0,00	0.00	0.00580037	0.00	1.00
Pos5 Process A.Queue	0.03461345	0,01	0.01447481	0.06610266	0.00	2.00
Pos6 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos7 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Pos9 stopper.Queue	0.00	0,00	0.00	0.00	0.00	0.
Process A.Queue	0.00	0,00	0.00	0.00	0.00	0.
Process B.Queue	0.00	0,00	0.00	0.00	0.00	0.

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Figure 33: Page 3/4 ARENA report

20:02:45 **Category Overview** juin 14, 2021

Values Across All Replications

Unnamed Project

Replications: 10 Time Units: Minutes

Resource

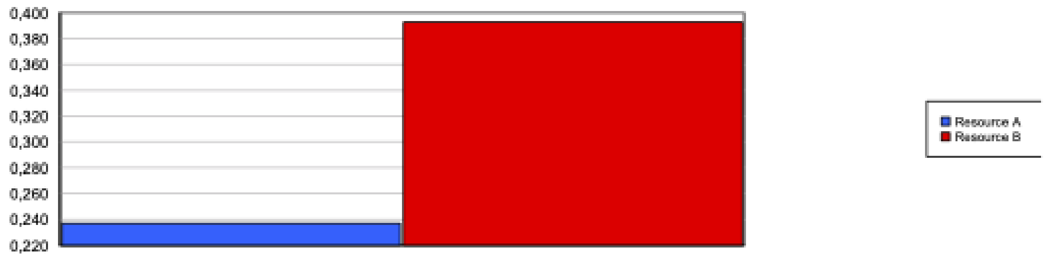
Usage

Instantaneous Utilization	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maxim Va
Resource A	0.2370	0,02	0.1939	0.2958	0.00	1.00
Resource B	0.3925	0,04	0.3063	0.5000	0.00	1.00

Number Busy	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maxim Va
Resource A	0.2370	0,02	0.1939	0.2958	0.00	1.00
Resource B	0.3925	0,04	0.3063	0.5000	0.00	1.00

Number Scheduled	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maxim Va
Resource A	1.0000	0,00	1.0000	1.0000	1.0000	1.00
Resource B	1.0000	0,00	1.0000	1.0000	1.0000	1.00

Scheduled Utilization	Average	Half Width	Minimum Average	Maximum Average
Resource A	0.2370	0,02	0.1939	0.2958
Resource B	0.3925	0,04	0.3063	0.5000



Total Number Seized	Average	Half Width	Minimum Average	Maximum Average
Resource A	57.0000	5,15	47.0000	71.0000
Resource B	63.0000	7,08	49.0000	80.0000

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Figure 34: Page 4/4 ARENA report