# POLITECNICO DI TORINO

MASTER'S DEGREE IN AUTOMOTIVE ENGINEERING

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**Design and optimization of an urban bus assembly line using a DES software**

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# Declaration of Authorship

Under my personal responsibility I hereby declare that I am the sole author of this thesis and that I have not used any sources other than those listed as references. I further declare that I have not submitted this work at Politecnico di Torino or at any other institutions in order to obtain a degree.

Gianluca Vitiello

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# Chapter 1

# Introduction

## 1.1 The project work

### 1.1.1 Description

The goal of this thesis work is to design an assembly line for an urban bus to be located in Spain with the use of a discrete event simulation software called Any-Logic.
The assembly line has been modelled in the software environment and simulated to define the improvements necessary to increase the process efficiency and the compliance with expected targets.
Different process parameters and input data are employed to simulate scenarios and match real cases situations. This work has been developed with the Polytechnic University of Madrid and in particular with the INSIA Institute.
This research center develops several projects and studies related to the automotive industry and it provides technological support for companies and public administrations, consultancy services, tests and certifications. The current main research areas at INSIA are related to accidentology, biomechanics, safety, intelligent systems, alternative propulsion and computational mechanics.
The choice of designing an assembly line for urban buses lays in the fact that its market plays an important role for both the Italian and Spanish automotive industry.
The bus assembly line is designed for a second phase manufacturing company, known as body builder.
The core business of this company is related to the assembly of the complete buses for final costumers or even semi-finished products further customizable by other companies.

The bodybuilder performs the manufacturing process of the body structure which is then assembled on underbody chassis supplied by an external company; the same occurs for other main vehicle components as for example the powertrain, the driveline and the gear box.
This type of company is very common within the Spanish bus manufacturing industry which counts a very large number of medium-small sized companies that work in partnerships with big European bus makers.
During the assembly process the supplied chassis are processed and adjusted in order to be employed to produce buses of different lengths.

FIGURE 1.1: UPM and INSIA

The line presented in this project work is designed to operate in a similar framework which also requires flexibility in terms of production mix and rate, adopting some standards typical of Spanish bus manufacturing industry.
The final line layout has been obtained performing several simulations using AnyLogic and implementing a series of discrete event simulations: these simulations have been useful to establish important line parameters as the number of parallel machines and the required buffers sizes between the workstations.
In addition other aspects of the line are analysed, in particular the main typologies of material handling equipment are presented and the necessary workforce for the bus assembly activities has been computed.
In the end, it has been possible to obtain a preliminary evaluation of the floor area required for the assembly line with the use of AutoCAD.
This analysis has permitted to integrate the designed line with the main employees facilities and auxiliary areas achieving the final plant layout.

### 1.1.2 Methodology

The work has been developed exploiting the past experience and data available at the INSIA institute in the field of the bus production.
The assembly steps and time durations have been validated by a Spanish bus manufacturing company with a profile aligned to the ideal target company for which the line is designed.
The choices related to production parameters have been selected using as reference some standards in the bus manufacturing industry and in particular about the Spanish one, as for example the working shifts and production rate. Once obtained the line structure model, simulations have been carried on using AnyLogic and the whole model has been later updated introducing sources of variability to bring it closer to a real case situation.
The final layout has been obtained optimizing the line structure in order to achieve a desired production target with respect the different product mixes. This optimization process has been conducted collecting data from the software and cycling implementing the desired modifications to reach the desired line performances.

### 1.1.3 Objectives

The objectives of this thesis work are to present the main choices that have to be made while designing a line and to offer an overview about the bus manufacturing processes and features.
Besides, this works aims at presenting the main benefits of the simulation modelling and highlighting its efficiency in the solution of real case problems.
This framework has been exploited to simulate different working conditions, line layouts and input parameters, offering a wide overview about possible scenarios in a complete risk free environment. This possibility increases the design process efficiency in many applications, making this work useful to be employed in a wider industrial scenario.
In the end, the computation of the floor area of the assembly plant is intended as

a tool to offer a more complete comprehension of the industrial environment surrounding the line. It is a preliminary step in design process of the whole facility.

## 1.2 Bus market

### 1.2.1 European trend

The choice of designing an assembly line for urban buses lays in the fact that its market plays an important role for the whole European automotive industry.
More than 50 % of all European public transport journeys are made by urban and suburban buses and the market has a positive trend of growth in Europe due to the increasing demand for mobility inside and outside the cities.
In UE + EFTA more than 46.000 buses (GVM $\geq$ 3,5 t) have been registered during the 2019 with a 1.8% of growth with respect the 2018.
Italy represents the fourth European market with 4.249 new registrations in 2019 with a loss of 7,1% with respect 2018.
The first five European markets for number of new registrations are France ( 6.780 units, +8,8% ), UK (6.628 units, -11,9%), Germany (6.437 units, -3,7%), Italy and Spain (3.261, -2%) [1].
Anyway in several countries the trend of new registrations can dramatically change from year to years and even within the year itself: this occurs due external factors like Government policies or fleet change request from municipalities and as a result the bus demand is not constant in time.
In Italy for example, before the reduction of 2019, in 2018 more than 30% of new buses have been registered with respect 2017.
In the end it is relevant to underline that more than 85% buses have a diesel propulsion system even if hybrid and electric buses market is growing due to the incentives given by country governments and regulations to the employment of more sustainable source of energies.
In Italy the urban bus registrations accounts for the most of total number of registrations, confirming the strategic importance of this product for the whole bus market.

TABLE 1.1: New buses registrations in Europe, ACEA data

| Country | 2015 | 2017 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|
| France | 7.345 | 6.593 | 6.329 | 6.230 | 6.780 |
| UK | 8.483 | 9.140 | 8.342 | 7.523 | 6.628 |
| Germany | 6.137 | 6.683 | 6.697 | 6.687 | 6.437 |
| Italy | 2.419 | 2.791 | 3.357 | 4.573 | 4.249 |
| Spain | 2.617 | 3.299 | 3.527 | 3.329 | 3.261 |
| EU + EFTA | 41.593 | 43.064 | 43.510 | 44.192 | 46.174 |

TABLE 1.2: Bus registrations in Italy divided by type, ANFIA data

| Bus type | Units | % |
|---|---|---|
| Urban city buses | 731 | 31,2 |
| Suburban buses | 499 | 21,3 |
| Touristic buses | 596 | 25,4 |
| Minibuses | 319 | 13,6 |
| School buses | 198 | 8,5 |
| Total | 2343 | 100 |

In Table 1.2 is reported the number of new registrations in Italy divided for purpose and working area according to ANFIA association for the first six months of 2019 [2].

### 1.2.2 Italian domestic production

In Italy the domestic production has deeply changed through the past two decades. The data elaborated by ANFIA report that only 627 buses, were produced by Italian bus maker in particular Iveco and Menarinibus ; in 1999 the produced buses were more than 3000 [2].
The reasons behind this negative trend have to be found in the economic-financial crisis post 2008 and also the lack of planning by the Government in determining the quality and quantity of local public transport services with respect the growing mobility and the necessity of reducing urban traffic, creating a viable alternative to private transport.

This has been done in several other European countries in which in fact the domestic bus production has grown through the years.
The lack of programming and vision resulted in an impoverishment of the public urban transportation in terms of offered service and it almost led to the loss of sector which has always been relevant to the whole Italian automotive industry

### 1.2.3 Spanish domestic production

In Spain, on the contrary, the situation is quite different since the domestic production is higher compared to the Italian one. Even though the market of new registrations is smaller, more bus manufacturers companies are present in Spain, in particular body builders.
There are more than 3000 companies in Spain that are currently employed in the field of the passengers transportation and the main bus manufacturing companies are associated into the ASCABUS association which groups: Ayats, Beulas, Burillo, Camelsa, Castrosua, Ciscar, Ferqui, Icas, Icasa, Indecasa, Irizar, Noge, Obradors, Silgar, Maiso, Ugarte, Unicar. The Spanish body builders export
s almost 50% of the bus bodies it produces and it creates stable employment also allowing the provision of a basic service for the population: public transport. In 2019, ASCABUS's associates invoiced more than 679 billion euros with a production of more than 3.800 buses. Considering the whole European bus bodybuilding industry, 11 companies are present on the Spanish territory accounting for 22% of the industry in the sector.
In conclusion, it is clear that the Spanish bus industry is very relevant for the whole country representing an attractive business with a very likely growth in the following years.

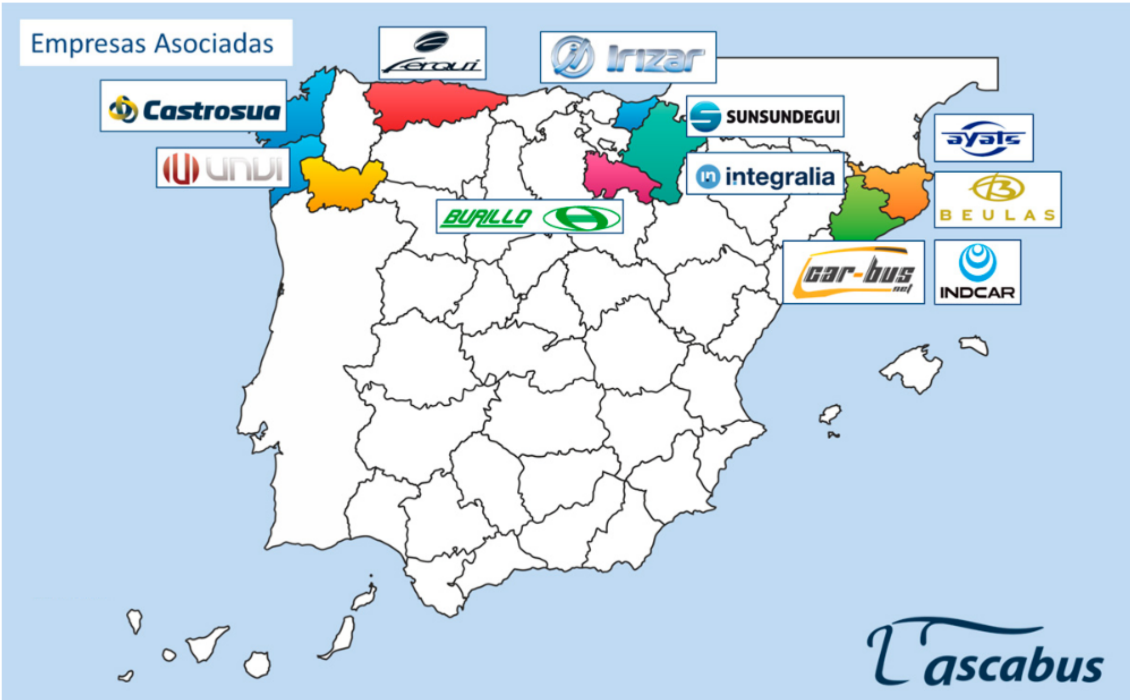



FIGURE 1.2: Bus manufacturing companies location in Spain

# Chapter 2

# Urban bus assembly process

## 2.1 Layout choice

### 2.1.1 Layouts overview

The first step for the design of an industrial manufacturing process is the layout choice. A production system can be arranged according three main typologies of process layouts:

- Line
- Shop
- Fixed position

The choice among these three layouts has to be done considering product and processes characteristics, material handling equipment required, production rate and necessity for production flexibility.
The assembly line layout is based on the idea that the stages needed for the assembly process are arranged in a sequential line.
Machines are dedicated to the production of a single product or a product family with high production rates but it provides low flexibility and thus low possibility of assembling products different from each other.
The assembly shop requires that the product flow does not follow a fixed path through the departments (called shops) thus several internal flows and routings are present inside them. Machines are grouped together inside the shops according to the technological affinity of the products that have to be assembled or by similarity of the machines themselves. The result is a medium/lower production rate but with the possibility of assembling different types of products.

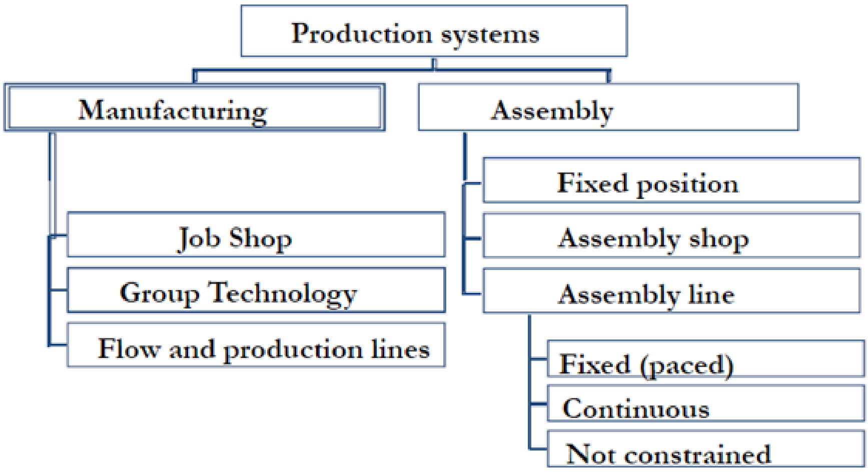



FIGURE 2.1: Industrial layouts

In the end, the fixed position assembly provides that the product that has to be assembled keeps a fixed position while components, tools and workers converge to the assembly site.
It certainly allows to have high flexibility about product characteristics but the production rate is small; it is suitable for big and heavy products (aircrafts, tool-machines etc).

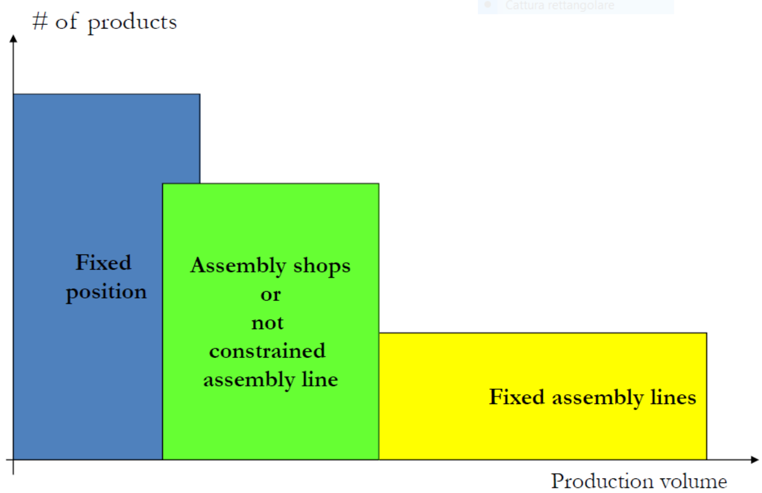



FIGURE 2.2: Industrial layouts features

### 2.1.2 The line layout

The assembly layout chosen for the bus is clearly the line typology because, compared to the other systems, it allows to:

- Reduce the total production time
- Reduce the total material transportation cost and time
- Reduce the work in progress
- Offer the highest efficiency in the productivity
- Improve the exploitation of plant area
- Perform time and method analysis to monitor productivity
- Transport materials and products in a continuous way

Those characteristics are suitable for the assembly of a product like an urban bus which is heavy and not to so easy to move inside the plant and whose assembly process requires dedicated machinery and material handling devices.
Even though the daily production is quite low, the line is the only layout that allows to reach this production goal since the assembly time required is considerable.
The lack of flexibility is not an issue in our case since the plant must be able to produce one typology of product or at least similar products for which the assembly routing is practically the same.
According to the time lag after which the product has to be transferred to the following stations, the assembly line can be further classified into three types:

- Fixed
- Continuous
- Not constrained

In the fixed assembly line, the product is stopped in each station for a fixed amount of time while in the not constrained type this time is not fixed and varies according to the station, leading to the formation of buffers between stations; the continuous type does not require the product to be stopped in the stations, flowing continuously through the line.

The designed line, due to the different duration of the activities performed in the workstations is a not constrained typology.

### 2.1.3 Production line parameters

It is useful to present the definitions of some relevant production parameters that will be later exploited in the description of the assembly process and also in the simulation results analysis:

- Workstation:defined portion of the line where one or more parallel machines are collected
- Throughput $TH$: average quantity of non-defective parts produced per unit time
- Cycle time $CT$: mean time a part spends in the line
- Work in process $WIP$: inventory in the routing
- Bottleneck rate $r_b$ : production rate of the workstation with the highest utilization
- Raw process time $T_0$ : sum of the process times of the workstations in a line
- Critical work in process $W_0 = r_b \cdot T_0$ : level of WIP providing the maximum throughput and the minimum cycle time in a line

Finally, it is worth to remember the Little's law which is an important relation between the work in progress, the throughput and the cycle time:

$$WIP = TH \cdot CT \tag{2.1}$$

## 2.2 The urban bus

### 2.2.1 European vehicles classification

In order to have a better understanding of the main features of an urban bus it is useful to recall the vehicles classification based on the United Nations Economic

Commission for Europe standards. The UNECE is a commission under the jurisdiction of the United Nations Economic and Social Council with the aim of promoting economic cooperation and integration among its Member States.
The classification provides a harmonization of vehicle regulations and it is mainly based on:

- Vehicle structure (GVM, number of wheels)
- Vehicle purpose

TABLE 2.1: Bus registrations in Italy divided by type, ANFIA data

| **Category** | **Description** |
|---|---|
| L | Motor vehicles with less than four wheels ) |
| M | Four wheels vehicles used for the carriage of passengers |
| N | Four wheels vehicles used for the carriage of goods |
| O | Trailers (including semi–trailers) |
| T | Agricultural and Forestry tractors |
| G | Off-road vehicles |
| SA/SB/SC/SD | Special purpose vehicles |

The M category vehicles are divided into:

- M1:Vehicles used for the carriage of passengers and comprising not more than 8 seats in addition to the driver's seat
- M2: Vehicles used for the carriage of passengers, comprising more than eight 8 in addition to the driver's seat, and having a maximum mass not exceeding 5 tonnes.
- M3: Vehicles used for the carriage of passengers, comprising more than 8 seats in addition to the driver's seat, and having a maximum mass exceeding 5 tonnes

The buses are M2 and M3 vehicles while a typical passenger vehicle is M1. Buses with a capacity exceeding 22 passengers are further classified into:

- Class I: Vehicles constructed with areas for standing passengers, to allow frequent passenger movement.
- Class II: Vehicles constructed principally for the carriage of seated passengers and designed to allow the carriage of standing passengers in the gangway and/or in an area which does not exceed the space provided for two double seats.
- Class III: Vehicles constructed exclusively for the carriage of seated passengers

Therefore, a urban bus is mainly a Class I vehicle since the working environment is the city road but on some particular lines also Class II vehicle can be employed; a vehicle may be also regarded as belonging in more than one class and in such a case it may be approved for each class to which it corresponds [3].

### 2.2.2 Bus dimensions

The assembly line is designed to comply with the production of urban buses of different dimensions. It is relevant to analyze the external bus dimensions in order to properly define the necessary workstations floor occupation to guarantee the correct space for the assembly activities.
Bus width is commonly fixed at 2550 mm, which is the maximum value defined by the European Community while the length can vary sensibly.
In order to have an overview about the most common bus lengths present on the Spanish urban roads, the EMT fleet composition has been analysed.
The "Empresa Municipal de Transportes de Madrid" is the company which manages the public urban transport in the city of Madrid with a fleet that consists of around 2.000 vehicles which work on more than 200 urban lines.
The bus lengths range from a minimum of 5,200 mm up to 18,000 mm and heights from 2,850 up to 3,400 mm. They are all single decker vehicles and they are sub classified according to size and purpose:

- Standard
- Articulated
- Minibus

- Midibus
- Airport Express

Analysing the fleet composition it is possible to see that the most common bus length is the 12 m; this information has been used as a starting point of the definition of the different assembly line production mixes described in the following pages.

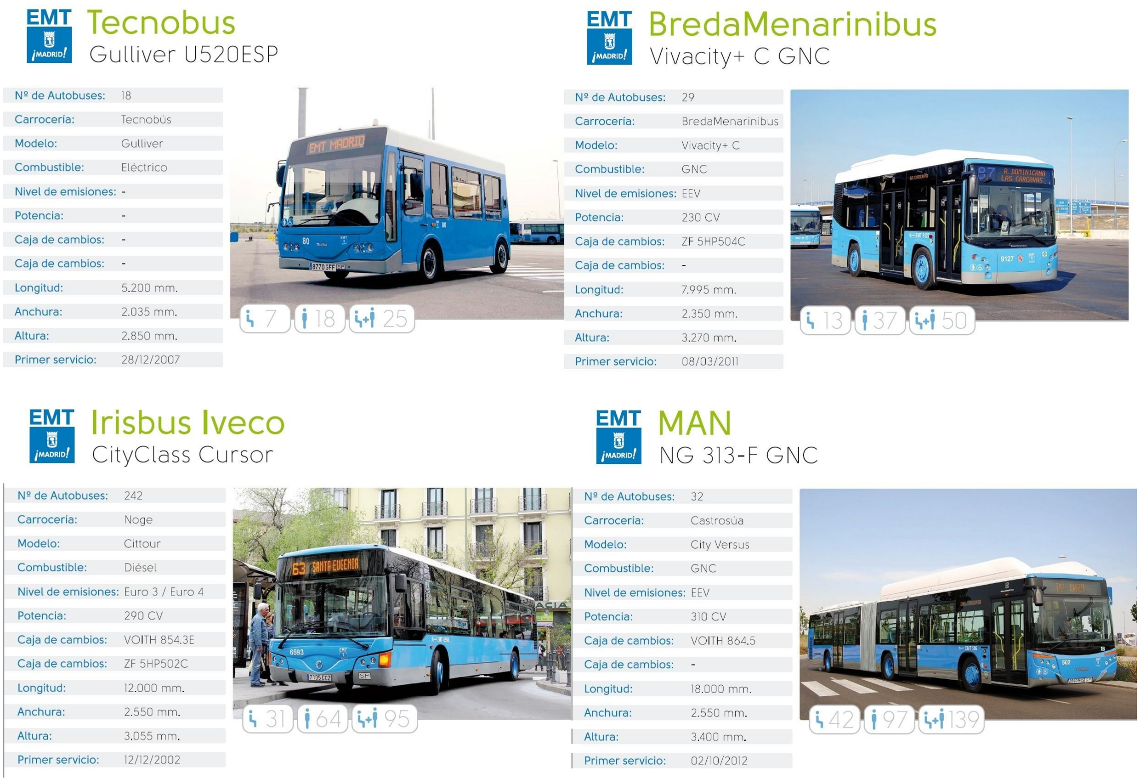
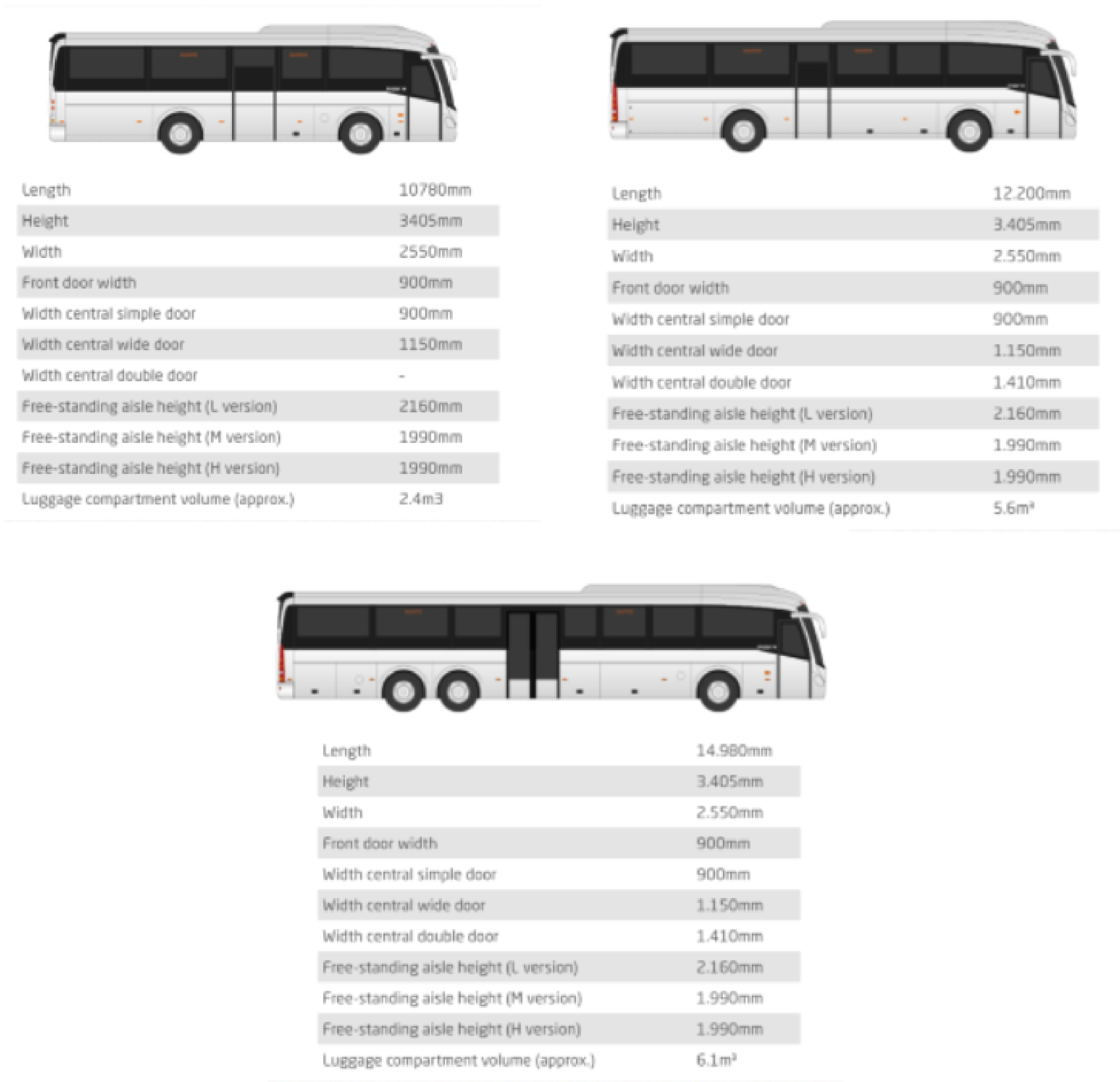



FIGURE 2.3: Examples of EMT buses, available at [6]

Bus manufacturers often offer the same product in different length variants. In the designed line the assembly process involve different bus lengths which belonging to the same product family sharing all the production steps.
This approach offers the possibility to the company to increase its product portfolio complying with the different market needs and request.
The Spanish Irizar, for example, offers most of its products in different length configurations; in Figure 2.4 an example of some of the existing configurations of the i4 model has been reported.



| | |
|---|---|
| Length | 10780mm |
| Height | 3405mm |
| Width | 2550mm |
| Front door width | 900mm |
| Width central simple door | 900mm |
| Width central wide door | 1150mm |
| Width central double door | - |
| Free-standing aisle height (L version) | 2160mm |
| Free-standing aisle height (M version) | 1990mm |
| Free-standing aisle height (H version) | 1990mm |
| Luggage compartment volume (approx.) | 2.4m3 |

| | |
|---|---|
| Length | 12.200mm |
| Height | 3.405mm |
| Width | 2.550mm |
| Front door width | 900mm |
| Width central simple door | 900mm |
| Width central wide door | 1.150mm |
| Width central double door | 1.410mm |
| Free-standing aisle height (L version) | 2.160mm |
| Free-standing aisle height (M version) | 1.990mm |
| Free-standing aisle height (H version) | 1.990mm |
| Luggage compartment volume (approx.) | 5.6m³ |

| | |
|---|---|
| Length | 14.980mm |
| Height | 3.405mm |
| Width | 2.550mm |
| Front door width | 900mm |
| Width central simple door | 900mm |
| Width central wide door | 1.150mm |
| Width central double door | 1.410mm |
| Free-standing aisle height (L version) | 2.160mm |
| Free-standing aisle height (M version) | 1.990mm |
| Free-standing aisle height (H version) | 1.990mm |
| Luggage compartment volume (approx.) | 6.1m³ |

FIGURE 2.4: Irizar i4, available at [7]

### 2.2.3 Bus structure

In order to better define and understand important steps of the bus assembly process it is useful to recap the main types of vehicle structure.
In automotive industry there are 2 main configurations:

- Integral frame
- Body on frame

The body on frame is the oldest and simplest configuration nowadays employed only for some heavy duty, off road and commercial vehicles. Its structure is composed of two distinct elements:

- The under body chassis
- The body structure

The under body chassis typically consists of a frame element which allows the connection and support of suspensions, power train, gearbox, steering system and other mechanical elements. This frame can have different shapes but for heavy duty and commercial vehicles the ladder frame is employed; it is composed of two long side members interconnected by cross elements. The body is instead the main supporting elements for the upper part of the vehicle and is connected to the frame using both rigid and flexible mounts.
The integral frame is a more modern and sophisticated solution, currently the standard for passengers cars, in which the body and chassis frame are integrated in a unique supporting element that overcomes typical problems and constraints of the body on frame structure: the higher vehicle weight, the higher floor height and the reduced lateral stability.
Besides, in the integral frame the torsion resistance is generally higher improving vehicle handling.
Anyway this configuration has some disadvantages: high manufacturing cost, higher repair cost and less design flexibility.
Some vehicles, as the urban bus, adopt a hybrid structure: the semi-integral frame.
In this configuration the chassis is split in a front and rear part and the central ladder frame is substituted by the lower part of the body structure; the body is not a shell structure simply placed on top of the chassis anymore but is integrated with it.
In the body builder plant the chassis length is adjusted before the body drop station to match the sizes of the assembled buses by removing central longitudinal beams used for transport operations, highlighted in yellow in Figure 2.5.

FIGURE 2.5: Semi integral frame, available at [8]

This solution allows to overcome some disadvantages of the body on frame structure as for example the higher weight and floor height offering higher design flexibility and the possibility of lower repair costs.
Nowadays the semi integral frame solution has become a common standard in the bus manufacturing industry and several Spanish body builders have changed their manufacturing process to comply with it.
The body is a steel element composed of 6 main modules:

- Floor
- Left and right sides
- Front and rear
- Roof

Each module is fixed to each other through welding, riveting and screwing and in particular the roof and sides modules are jointed using a male-female coupling.
They are assembled in the first line station and in the following one the whole

structure undergoes a chemical treatment to increase the corrosion resistance. Additional steel supporting elements are present in corners for increase the overall structure strength. The floor module is integrated with the two chassis parts and its length defines the overall bus length.
Typical bus structure in the images below, courtesy of INSIA Institute.

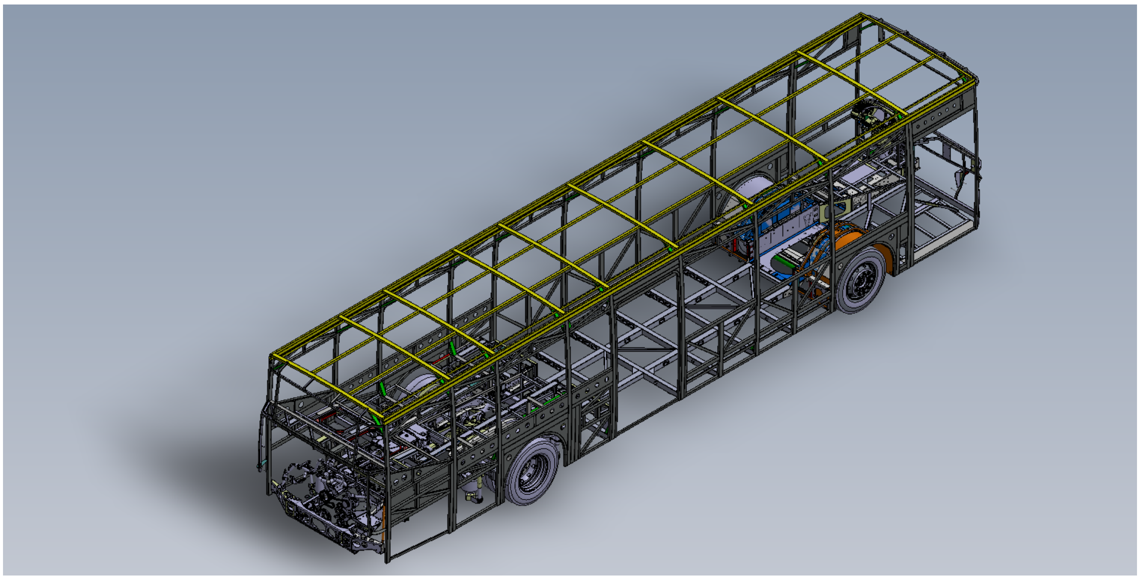


FIGURE 2.6: Full view

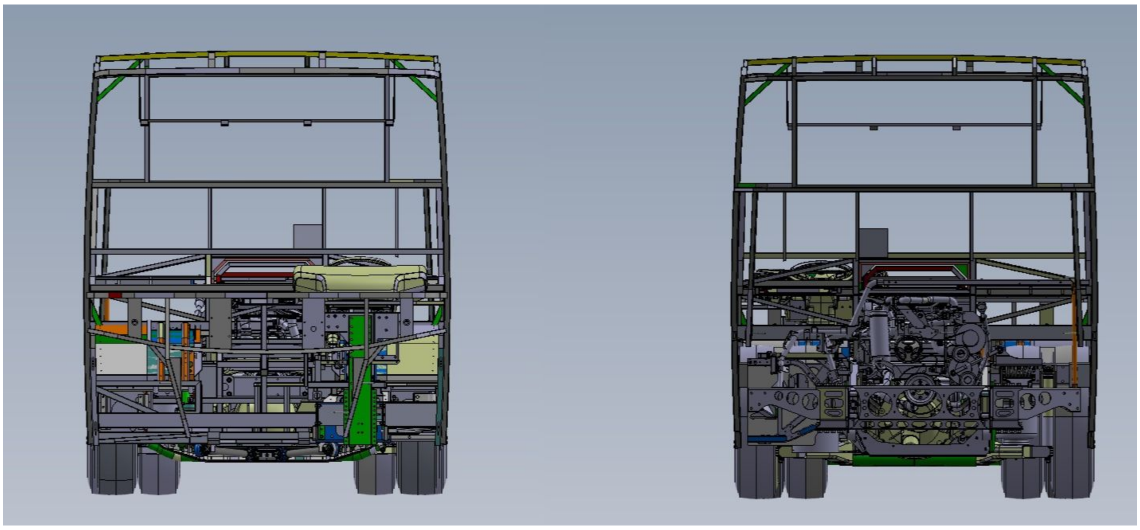


FIGURE 2.7: Front and rear view

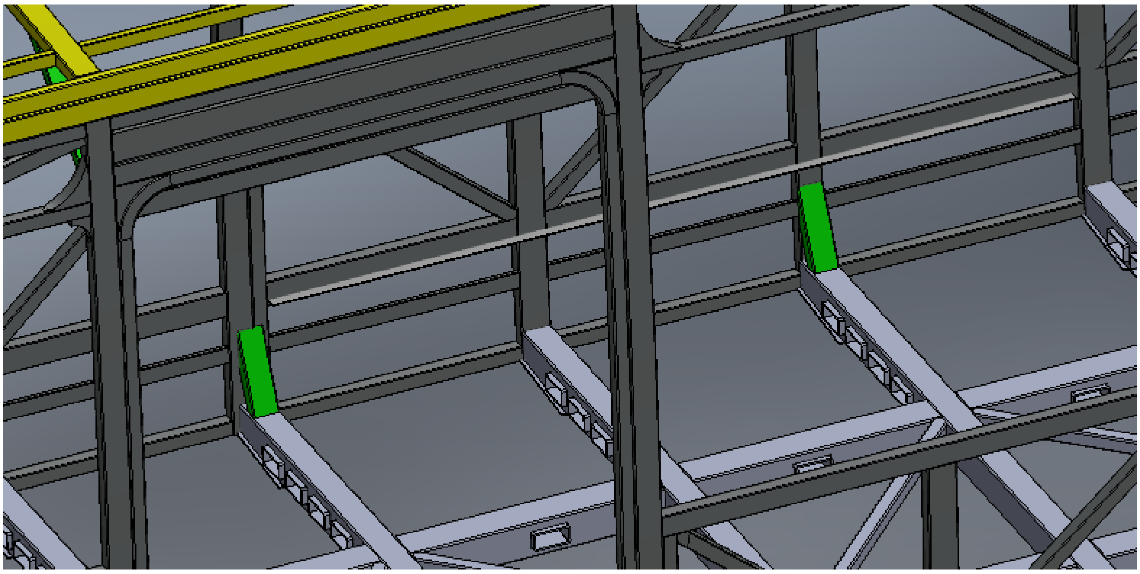


FIGURE 2.8: Supporting elements between floor and side modules

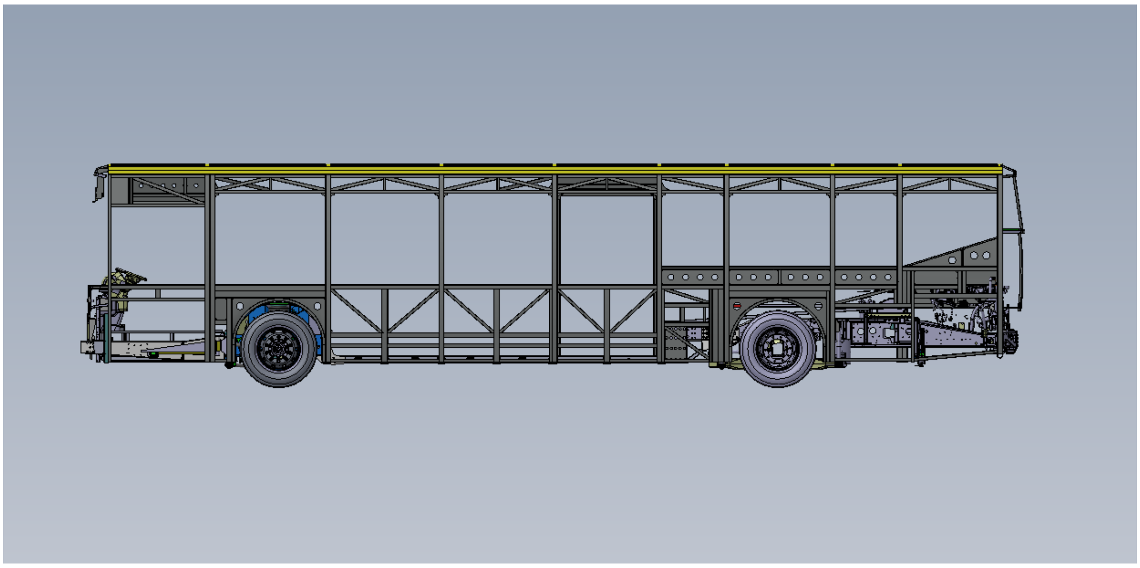


FIGURE 2.9: Side view

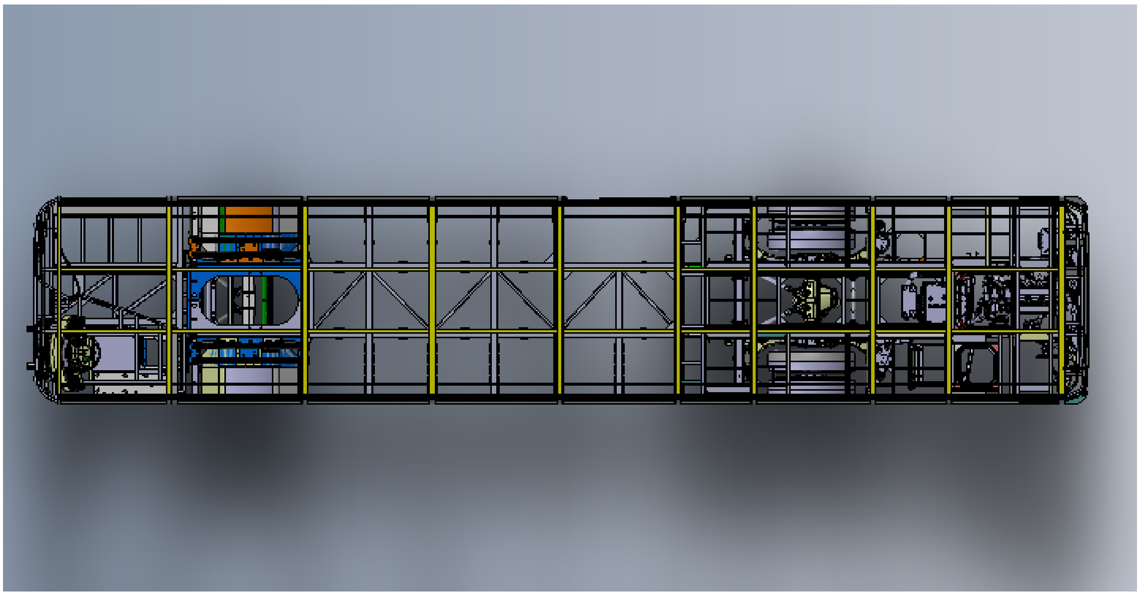


FIGURE 2.10: Top view

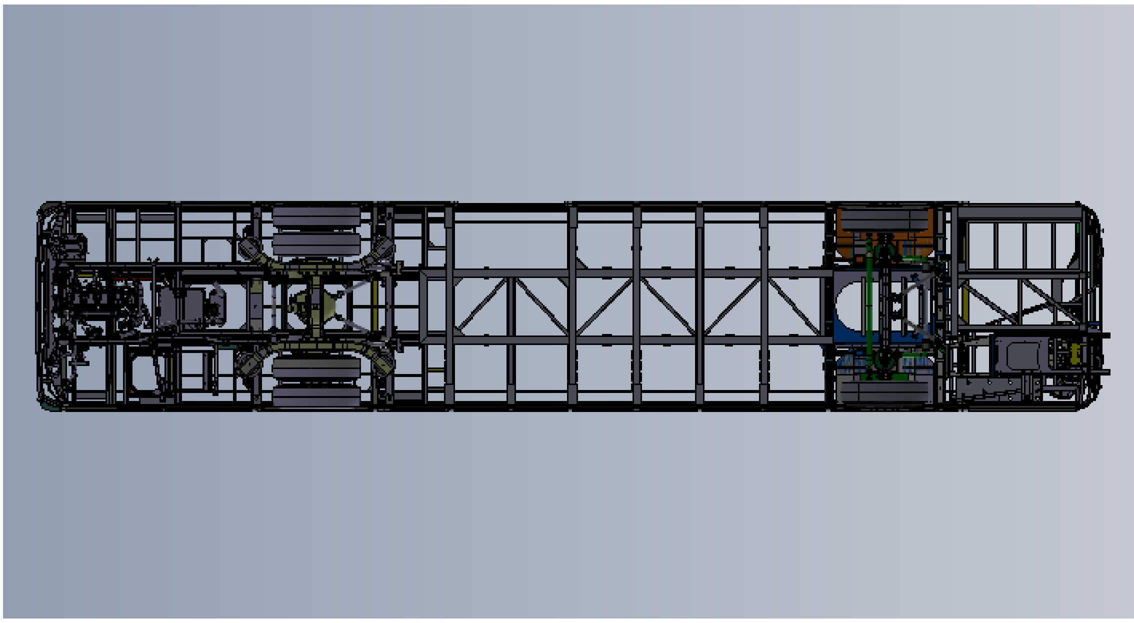


FIGURE 2.11: Bottom view

### 2.2.4 Assembly process description

The whole bus assembly process is performed in 10 main workstations:

- OP 10 - ASSEMBLY OF BODY STRUCTURE
- OP 20 - ELECTROPHORESIS TREATMENT
- OP 30 - PANELS FIXING
- OP 40 - COAT PAINTING
- OP 50 - BODY DROP
- OP 60 - INTERIORS/FINISHING
- OP 70 - STYLE PAINTING
- OP 80 - DRIVING TEST
- OP 90 - BRAKE TEST
- OP 100 - SHOWER TEST

**OP 10**
During this step the assembly of the body steel structure of the bus is performed. This element guarantees rigidity to the upper part of the vehicle and represents the starting point of the assembly process; in the first part of the line all the activities are related to this element till the body drop (also called "marriage") that occurs in OP50 and during which the top structure will be fixed to the chassis frame.
The body structure is composed of 6 main modules: floor, sides, roof, front and rear part and they need to be positioned on particular rack equipment that allows the operator to easily fix them together. The assembly is performed mostly using a manual welding process but also through riveting and screwing and exploiting a coupling system for sides and floor modules which are provided with a peculiar design.
The operations take place in 2 sub stations, one for all the assembly processes and to allow the operators to inspect the quality of the welding joints:

- OP11
  - Positioning of floor module on the central rack using overhead crane
  - Positioning of both side modules on side racks using overhead crane
  - Welding of the 3 modules
  - Positioning of roof module (male and female coupling) and welding with side ones
  - Positioning and welding of front and rear modules with roof and floor modules
- OP12
  - Inspection
  - Positioning of the structure on trolleys for the following station

**OP 20**

The steel top structure obtained through welding in the previous station has a rough surface which need to be treated to remove flaws and imperfections and also to increase the resistance to corrosion; this last process is called electrophoresis and is performed immersing the structure in several pools placed one after the other using an overhead crane.
The pools are full of water and chemical elements that react with the steel structure reaching the right corrosion resistance; the operations are interspersed with rinsing to wash and prepare the structure for the following treatment.
The process takes place in 9 different substations: 1 for pre-treatment polishing where the operators manually prepare the structure and other 8 pools in which the immersions are performed. The sequence of tasks can be summarized as:

- OP21
  - Pre-treatment polishing
  - High pressure rinsing
- OP22
  - Degreasing
  - Rinsing 1
- OP23
  - Surface conditioning

- OP24
  - Phosporization
  - Rinsing 2
- OP25
  - Process spraying
  - Rinsing 3
- OP26
  -Electrophoresis
- OP27
  -UF1/UF2 Rinsing
  - Rinsing 4
- OP28
  - Hot dry process and curing
- OP29
  - Cooling

**OP 30**
In this station some of the external panels are fixed to the body in advance of the painting station. Before being glued to the steel structure, the panels undergo a stretching treatment through the use of mechanical or heating tension to make them stretch for 0.8-1‰; this process reduce the plane deformation of panels guaranteeing a reduction of vibrations and noise during the bus travel.
The activities takes place in 2 sub stations:

- OP31
  - Panels stretching
  - Panels gluing (side, rear, front and top ones)
- OP32
  - Positioning of frame structure for windows
  - Inspection

**OP 40**

This represent the first of two painting stations, during which a preparatory coating paint layer is placed on the bus structure. The operations are performed manually and are divided into 3 sub stations:

- OP41
  - Cleaning and dry sanding
- OP42
  - Application of primer coat
- OP43
  - Drying process
  - Inspection

**OP 50**

In this station the marriage between the body structure and the chassis takes place. The chassis frames (which are manufactured by an external company) are adjusted in length to match the size of the different assembled bus; this preparatory activity is performed before the body reaches this station.
The sequence of operations takes place in 5 sub stations:

- OP51
  - Initial wiring and pipes positioning
- OP52
  - Assembly of body structure on the chassis with an overhead crane
- OP53
  - Whole structure lifting with column lifts to allow fixing of underbody mechanical parts (differential, steering systems etc.)
- OP54
  - Engine fixing
- OP55
  - Inspection

**OP 60**

In this station the finishing operations take place. It represents the end of assembly activities in the strict term, where the vehicle external and internal trims are

assembled as well as passenger transportations equipment as seats, handles etc.
The operations are held in 6 sub stations, divided for category of assembled items:

- OP61
  - Electrical wirings, lighting, sound, safety systems installation
- OP62
  - Air conditioning system installation
- OP63
  - Interior panelling (floor, sides, roof) installation
- OP64
  - Seats, seats anchorages installation
- OP65
  - Windows installation
- OP66
  - Pneumatic installation e.g. doors, ramps, etc

**OP 70**
This in this station the final painting activities are performed as well as applications of stickers and external styling customization.
It is divided into 3 sub stations:

- OP71
  - Final paint application
- OP72
  - Drying process
- OP73
  - Vinyl stickers for styling and final inspection

**OP 80**
In this station the brake test is performed to analyse engine performances, working conditions of safety equipment, noise and exhaust emissions.
The operations are generally performed on a roller test bench.

**OP 90**
The vehicle is driven to analyse handling and driving response on different road surfaces. This test is performed on an outside track.
**OP 100**
In the end, the bus is driven inside a shower test chamber placed outside the line. This process allows to verify that all sealing systems prevent liquids to go inside some vehicle compartments.

## 2.3 Process parameters

### 2.3.1 Deterministic time analysis

After having identified the main assembly steps, each time duration has to be defined to evaluate the cycle time of the whole process.
In this preliminary chapter a deterministic approach is carried on and the model has been implemented without any sources of variability: the times for each step of the process are always the same (simulation after simulation) in order to have a first estimation of how the model behaves.
In chapter 4 external sources of variability and probability distributions for steps duration are implemented into the model to refine its structure and bring it closer to a real case.
The considerations about the time durations presented in this chapter have been performed exploiting INSIA experience and background within the bus manufacturing industry, especially the Spanish one.
After a preliminary evaluation of the already available data present at the Institution, the resulting time durations have been validated from a Spanish bus manufacturer whose company profile is aligned with the target company for which the line is designed. The results of this analysis are relative to a 12 m long buses and are intended to be considered as average values.
Actually, the line is designed to host the assembly process of 3 different types of buses:

- 10 m buses
- 12 m buses

- 15 m buses

The 3 bus configurations share all the productive steps and, in order to evaluate the cycle time differences due to the different size, some of the steps durations have been increased or decreased with respect of the reference values.
The duration of each task relative to the reference 12 m are:

**OP 10**

- OP11
  - Positioning of floor module on the central rack using overhead crane: 20 min
  - Positioning of both side modules on side racks using overhead crane:40 min
  - Welding of the 3 modules: 30 min
  - Positioning of roof module: 20 min
  - Welding of roof with side ones: 30 min
  - Positioning of rear and front modules: 30 min
  - Welding of front and rear modules with roof and floor modules: 60 min
- OP12
  - Inspection: 20 min

TOTAL TIME: 240 min - 4 h

**OP 20**

- OP21
  - Pre-treatment polishing: 15 min
  - High pressure rinsing: 5 min
- OP22
  - Degreasing: 10 min
  - Rinsing 1: 5 min
- OP23
  - Surface conditioning: 5 min

- OP24
  - Phosporization: 5 min
  - Rinsing 2: 5 min
- OP25
  - Process spraying: 5 min
  - Rinsing 3: 5 min
- OP26
  - Electrophoresis: 10 min
- OP27
  -UF1/UF2 Rinsing: 5 min
  - Rinsing 4: 5 min
- OP28
  - Hot dry process and curing: 30 min
- OP29
  - Cooling: 30 min

TOTAL TIME: 140 min - 2,3 h

**OP 30**

- OP31
  - Panels stretching and gluing: 120 min
- OP32
  - Positioning of frame structure for windows : 100 min
  - Inspection:20 min

TOTAL TIME: 240 min - 4 h

**OP 40**

- OP41
  - Cleaning and dry sanding: 75 min
- OP42
  - Application of primer coat: 75 min

- OP43
  - Drying process: 60 min
  - Inspection: 20 min

TOTAL TIME: 230 min - 3,83 h

**OP 50**

- OP51
  - Initial wiring and pipes positioning: 180 min
- OP52
  - Assembly of body structure on the chassis with an overhead crane: 180 min
- OP53
  - Whole structure lifting with column lifts to allow fixing of under body mechanical parts (differential, steering systems etc.): 120 min
- OP54
  - Engine fixing: 120 min
- OP55
  - Inspection: 20 min

TOTAL TIME:620 min - 10,33 h

**OP 60**

- OP61
  - Electrical wiring, lighting, sound, safety systems installation: 120 min
- OP62
  - Air conditioning system installation: 60 min
- OP63
  - Interior panelling (floor, sides, roof) installation: 180 min
- OP64
  - Seats, seats anchorages installation: 30 min

- OP65
  - Windows installation: 240 min
- OP66
  - Pneumatic installation e.g. doors, ramps, etc:120 min

TOTAL TIME: 750 min - 12,5 h

**OP 70**

- OP71
  - Final painting application: 120 min
- OP72
  - Drying process: 120 min
- OP73
  - Vinyl stickers for styling: 120 min
  - Final inspection: 20 min

TOTAL TIME: 380 min - 6,33 h

**OP 80 - OP 90 - OP 100**

- Brake test: 15 min
- Driving test: 120 min
- Shower test: 15 min

Therefore, the total raw process time is 2.750 min - 45,83 h As mentioned before these re reference values and they have to be modified to obtain the raw process time of the other 2 types of buses assembled in the line.
The variations of the process time (with respect to the reference values of the 12 m bus) have been set as follows:

- An increment of 20% for the 15 m bus
- A decrement of 20% for the 10 m bus

Those variations are set only for the productive steps in which the size difference brings to an additional (or reduced) quantity of time that has to be devoted to the production step.
The operations involving a difference of time are:

- OP10 - Assembly of body structure
- OP30 - Panels fixing
- OP40 - Painting coating
- OP50 - Body drop
- OP60 - Interiors/Finishing
- OP70 - Painting styling

While no variations are required for:

- OP20 - Electrophoresis treatment
- OP80 - Brake test
- OP90 - Driving test
- OP100 - Shower test

TABLE 2.2: Steps duration for reference 12 m bus

| **Station** | **min** | **h** |
|---|---|---|
| OP10 | 240 | 4,00 |
| OP20 | 140 | 2,33 |
| OP30 | 240 | 4,00 |
| OP40 | 230 | 3,83 |
| OP50 | 620 | 10,33 |
| OP60 | 750 | 12,50 |
| OP70 | 380 | 6,33 |
| OP80 | 15 | 0,25 |
| OP90 | 120 | 2,00 |
| OP100 | 15 | 0,25 |
| Raw Process Time | 2.750 | 45,83 |

TABLE 2.3: Steps duration for 10 and 15 m buses

| **10 m** | | | **15 m** | | |
|---|---|---|---|---|---|
| Station | min | h | Station | min | h |
| OP10 | 176 | 2,93 | OP10 | 284 | 4,80 |
| OP20 | 140 | 2,33 | OP20 | 140 | 2,33 |
| OP30 | 192 | 3,20 | OP30 | 288 | 4,80 |
| OP40 | 184 | 3,07 | OP40 | 276 | 4,60 |
| OP50 | 500 | 8,33 | OP50 | 744 | 12,40 |
| OP60 | 600 | 10 | OP60 | 900 | 15,00 |
| OP70 | 304 | 5,07 | OP70 | 456 | 7,60 |
| OP80 | 15 | 0,25 | OP80 | 15 | 0,25 |
| OP90 | 120 | 2,00 | OP90 | 120 | 2,00 |
| OP100 | 15 | 0,25 | OP100 | 15 | 0,25 |
| Raw Process Time | 2.258 | 37,63 | Raw Process Time | 3.242 | 54,03 |

### 2.3.2 Working hours/day

For the line design purpose, the preliminary step is the definition of the number of yearly working days and the definition of the amount of working hours/day. Line characteristics and target performances are set in this design stage and then the obtained output is evaluated and optimized using the discrete event simulation software.

Generally speaking, the line characteristics and target performances have been defined according to the following criteria:

- Urban bus demand analysis
- Benchmarking of the competitor companies located on the Spanish territory
- Standards about Spanish bus manufacturing industry

As it has been shown in a previous chapter, the urban bus demand can vary in a relevant way from year to year but also within the year itself; the market demand is quite sensitive to a set of external factors like calls for tenders from municipalities or private institutions, government policies and it therefore cannot be considered always constant and stable.

Therefore, a flexible production rate is necessary and this could be achieved by changing the available working time during the year.

In order to properly match the market demand with the working load in the assembly line 2 different amounts of working hours/day have been selected.
This choice has been made in compliance with industrial standards, common in the Spanish bus manufacturing field:

- Case A consists of 2 daily production shifts and it is suitable for high demand periods. In this configuration the first longer shift lasts from 07:00 up to 15:00 while the second one from 15:00 up to 19:00
- Case B consists of 1 daily production shift and it is designed to provide a suitable production output for low demand periods. The production shift lasts from 07:00 up to 15:00 while from 15:00 up to 19:00 most of the production activities are suspended and the plant is open only for carrying on administrative tasks.

In Case A during the first shift of 7.5 h (considering 30 min break for lunch between 11:00 and 11:30) and second one of 4 h, the assembly plant produces at its maximum capability employing the whole workforce. In Case B the plant produces at its maximum capability with the whole workforce only during the 7.5 h shift in the morning. During the afternoon shift, whenever it is needed, only a reduced fraction of the workforce is present in the plant.
The total number of days devoted to each case is 130 days.
This choice leaves, which has to be validated using AnyLogic, leaves space to adjust the productivity of the line by changing the days devoted to Case A or B. In the end different combination of working days of the 2 cases will be presented in order to assess the potentialities of the line in different productivity cases.

### 2.3.3 Production rate

Another important target parameter to define is the line production rate.
According to the typology of company for which the line is designed and to the previous mentioned criteria the daily production rate has been set to 3 buses/day considering an average market demand of 780 buses/year.
This target output is medium-low with respect to other bus production plants present in Europe but is aligned with the production rate of quite important Spanish bus manufacturing companies.

This rate is also typical of a second phase manufacturing company, whose production process is generally performed mostly in a manual way. In order to comply with the requirements about the variable amount of working hours/day and the daily production rate the target throughput for the 2 different cases are:

- 3,5 buses/day for case A, with a takt time of 3,83 h/buses
- 2,5 buses/day for case B, with a takt time of 2,14 h/buses

The results are summarized in Table 2.4.

TABLE 2.4: Production parameters

| | | |
|---|---|---|
| Yearly working days | 260 | days |
| Yearly average market demand | 780 | buses/year |
| Daily average market demand | 3 | buses/day |
| Target TH case A | 3,5 | buses/day |
| Target TH case B | 2,5 | buses/day |
| Takt time case A | 3,83 | h/bus |
| Takt time case B | 2,14 | h/bus |
| Days for case A | 130 | days |
| Days for case B | 130 | days |
| Months for case A | 4,33 | months |
| Months for case B | 4,33 | months |

### 2.3.4 Product mixes

As mentioned before the line is designed to host the assembly process of three types of buses with different lengths.
As evaluated in chapter 1, the 12 m long bus is the product whose market demand is generally higher since it is more required by municipalities, like for example the EMT, due to the road geometrical constraints and for the higher passengers capacity with respect the 10 m length buses.
Therefore, the product mix 1 visible in Table 2.5 can be an example of a typical product mix for the line.

TABLE 2.5: Product mix 1

| **Buses length [m]** | **Quantity [%]** |
| --- | --- |
| 12 | 50 |
| 10 | 30 |
| 15 | 20 |

Anyway, the line must sustain an efficient assembly also in the case of different product mixes. The simulations that will be exposed in the following chapters take into account this aspect and they are carried on the basis of two other product mixes.
The product mix 2 present a higher quantity of the longest bus while the product mix 3 has a higher quantity of the shortest one.
These two other mixes, even if they are not always representative of a real demand, offer the possibilities to verify the line design even for more critical situations in terms of workstation utilization and target production.

TABLE 2.6: Product mix 2

| **Buses length [m]** | **Quantity [%]** |
| --- | --- |
| 15 | 50 |
| 12 | 30 |
| 10 | 20 |

TABLE 2.7: Product mix 3

| **Buses length [m]** | **Quantity [%]** |
| --- | --- |
| 10 | 50 |
| 12 | 30 |
| 15 | 20 |

# Chapter 3

# The model

## 3.1 Software modelling

### 3.1.1 Introduction

Modelling is a way through which it is possible to solve real world problems.
It is not usually efficient and affordable to perform lots of experiments with real objects to find the right optimization and solution and therefore it is useful to build a model that uses a modelling language representing the real system behaviour.
This process assumes abstraction and implies that the model is always less complex than the original system: we include the details we believe are important and leave aside those we think are not relevant. During the model building the abstraction level and the modelling language has to be chosen [4].
After building the model it is possible to start simulating it, exploring and understanding our system structure, testing how it will behave under a variety of conditions and comparing scenarios. After this analysis step we can finally obtain an optimization for our system.
The aim of modelling is to find the way from the problem to its solution through a risk free world where it is possible to make mistakes, undo things, rethink about the design, go back in time and start over again.

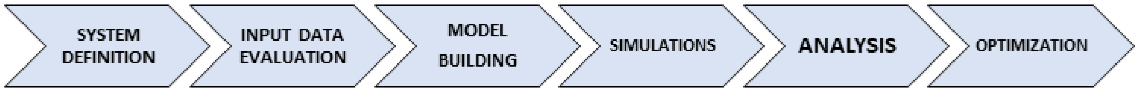



FIGURE 3.1: Modelling optimization process

### 3.1.2 Analytical Vs. Simulation Modelling

Microsoft Excel is a typical modelling tool used for strategic planning, sales forecasting, logistics, marketing or project management decisions: it is widely available, easy to update and it allows to add data and formulas to spreadsheet.
The technology behind spreadsheet-based modelling is simple allows to place inputs data in cells and view easily the data outputs in others with formulas and scripts linking the input and output values.
Besides various embedded features permit to perform parameter variation or optimization experiments.
However, there is a large class of problems where the analytic solution is either hard to find or simply does not exist. This class includes for example non linear systems or ones with not intuitive influences between variables [4].
Formulas that are good at expressing static dependencies between variables typically do not describe properly systems with dynamic behaviour.
That is why we use another modelling technology called simulation modelling to analyse dynamic systems. The simulation model creates the trajectory of the system state changes embedding the rules that define how to move from a current systems state to a future one. The model outputs are obtained and analysed while the simulation runs.

### 3.1.3 Advantages and applications of Simulation Modelling

Simulation modelling has five key advantages:

- 1. To allow to analyse systems behaviour and find suitable solutions to relative problems. It succeeds where analytic methods and linear programming fail.
- 2. Once that the abstraction level has been defined it is easier to develop a simulation model than an analytical one. It requires less time and the development process is scalable, incremental and modular.
- 3. The simulation model reflects the real system structure.
- 4. In a simulation model it is possible to keep track values within the level of abstraction, adding measurements and statistical analysis at any time.
- 5. This modelling typology has the ability to animate the system in time also offering a visual representation.

Simulation modelling has a wide range of applications. Figure 3.2 shows several simulation application areas sorted by abstraction level of the corresponding models.

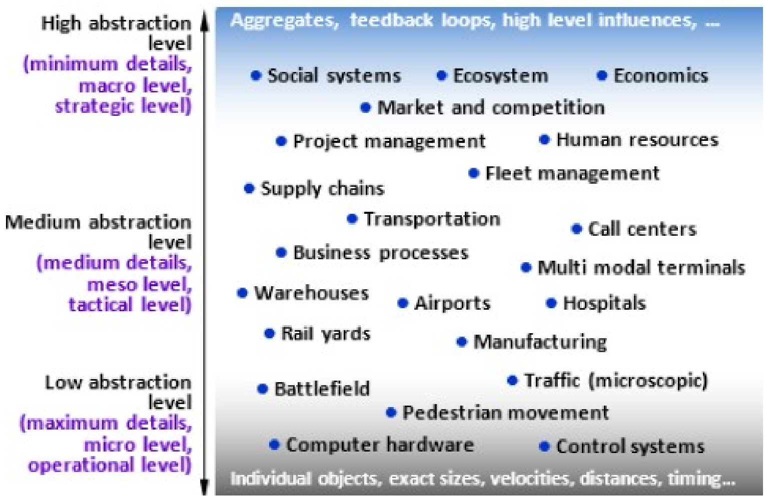



FIGURE 3.2: Typical applications for simulation modelling, from [4]

At the bottom of the image there are the physical level models which use a high detailed representation of real world systems. At this level it is possible to analyse systems physical interaction, dimensions and velocities: some examples are vehicles antilock brakes, the evacuation of fans from a stadium or the traffic level at a road intersection.
The top models have a high level of abstraction and they typically use aggregates such as consumer populations and employment statistics rather than single objects. Since their objects interact at a high level, they help in the understanding of relationships without the necessity of modelling the intermediate steps.
Other models have an intermediate abstraction level: in the modelling of a hospital emergency department we may be interested about physical space if we want to know how long it to walk to emergency room from a particular hospital department but the physical interaction among people in the building is irrelevant because we assume that the building is not congested. In a model of a call center, instead, we can model operations sequence and duration rather than their exact location.
Or, in the end, in a transportation model we can consider truck speed, but in a higher level of supply chain model we may simply assume that an order takes between seven and ten days to arrive etc.
For the previous considerations it is evident how the choice of the right abstraction level is relevant to the success of the modelling project.

### 3.1.4 DES Simulation

Simulation modelling can be performed using three methods:

- System Dynamics
- Discrete Event Modelling
- Agent Based Modelling

Each simulation method has a different abstraction level. System dynamics, for example, assumes very high abstraction and it is typically used for strategic modelling activities. Discrete event modelling are employed to work in medium and medium low abstraction level context. In the middle there are agent based models which can vary from very detailed models where agents represent physical

objects, to the highly abstract models where agents represent governments or competing companies.
It is also possible to find that the best way to model different parts of a system is to use different methods and, in these situations, a multi method model can be a suitable choice.

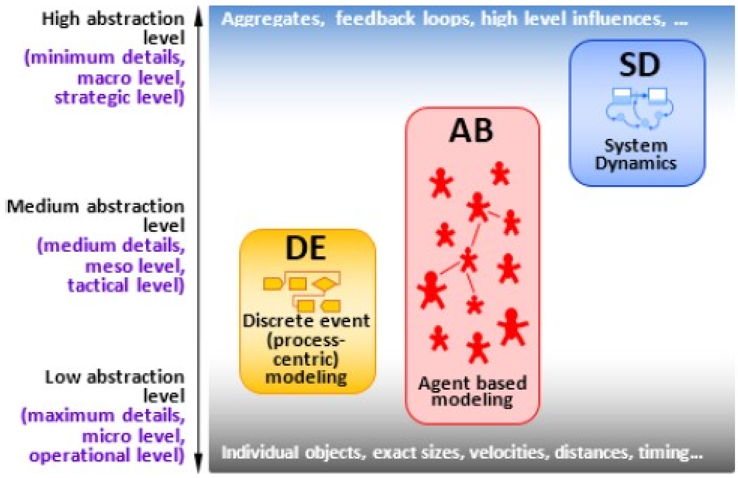



FIGURE 3.3: Abstraction levels of simulation modelling methods, from [4]

In 1961 the IBM engineer Geoffrey Gordon introduced GPSS, which is considered to be the first software implementation of a DES method.
The discrete event simulation (DES) models the operation and activities which take place in a system as a discrete sequence of events in time.
This sequence of events is modelled as a set of operations performed by agents (also called entities) and thus they include delays, resources, queues, branch selection etc. To properly describe the discrete event modelling it is useful to recall that the simulation modelling technique exploits the use of dynamic models that are suitable to represent the systems changes over time; on the other hand, a static simulation model represents a system state in a particular moment in time.
A discrete model is one in which the state variables change only at a discrete set of moments, while a continuous model is one in which they change continuously over time.
The employed software has also a graphical structure similar to flowchart diagrams where blocks represent operations.

In particular in AnyLogic the flowchart starts with a source block that generates agents and injects them into the system. It ends with a sink block that removes the agents once they have performed the operations.
Agents can represent several different entities like clients, pallets, vehicles, tasks, according to the level of abstraction .Resources represent staff, operators, machines, computer memory, equipment etc.
Service times and agent interarrival times can be deterministic or stochastic.
Simulation models that do not contain random variables are classified as deterministic and they have a known and defined set of inputs which will result in a unique set of outputs.
A stochastic simulation model, instead, has one or more random variables as inputs. Random inputs lead to random outputs and thus they can be considered only as estimates of the true characteristics of a model. Besides, the model must run for a specific amount of time or for a specific number of replications before it is able to produce meaningful outputs. Typical expected outputs from a discrete event model are:

- Machines and resources utilization
- System throughput
- Bottlenecks
- Queue lengths
- Time spent in the system by an agent
- Waiting times

Examples of applications for a DES model are:

- Improvement of process performances, stock out problems, material handling issues, breakdowns and wastes
- Plan changes: alternative investment ideas, cost reduction plans, optimum batch sizes, prioritization and dispatching logic for goods and services
- Training
- Decision making support

## 3.2 AnyLogic implementation

### 3.2.1 Software interface

AnyLogic interface can be partially customized but it mainly characterized by five main sections:

- Tool bar on the top
- Projects and Palette sections on the left
- The working spaces are placed in the central part
- Properties section on the right
- Console and Problems sections in the bottom part

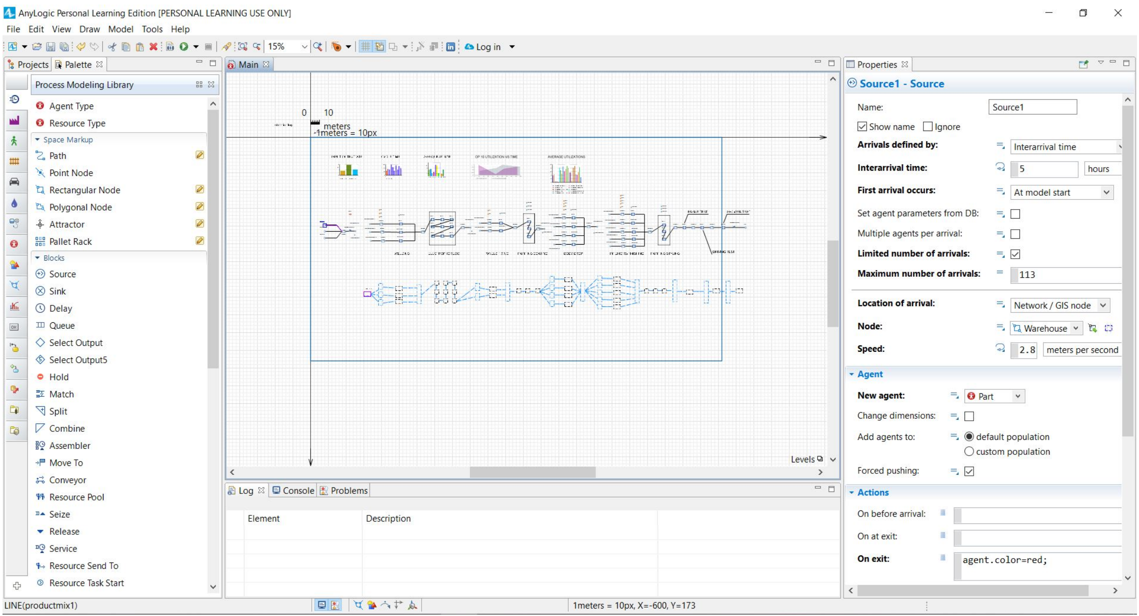



FIGURE 3.4: AnyLogic interface

The Tool bar embeds control functions for managing objects in the model, editing and saving the whole file, compiling the model code and then run the simulation. The help button offers an on online guide helpful to have an overview about the blocks functionalities and some examples models.

The Console and Problems sections allow, respectively, to show the output of

the model and to highlight eventual problems that prevent its execution. In fact, apart from mistakes in the connection of blocks, also problems relative to the Java programming language that represents the input code language of AnyLogic can occur too.
The Projects section shows the hierarchical structure of the model displaying all the different working spaces that compose the models (in the image below they are Main and Part) and the sub sections like the Simulation and the Database collection. The Palette section, instead, shows the libraries containing all the blocks useful to build the model; the blocks are dragged from this section and placed in the working space.
In this project work the Process Modelling, the Material Handling, the Agent, the Presentation and the Analysis library will be employed.

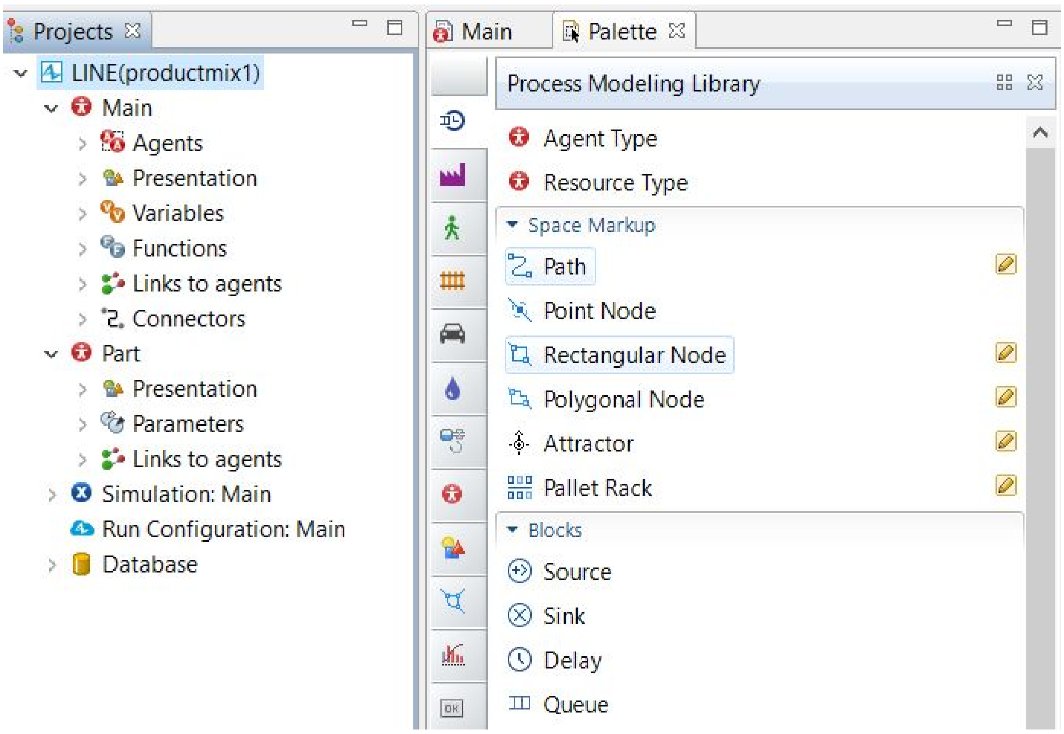



FIGURE 3.5: Projects and Palette

These blocks represent the backbone of the model structure which usually appear like a flowchart with the different blocks linked together creating a sequence of steps with a defined direction of progress.

Each block has a defined working principle and properties (shown usually on the right part of the interface) and input and output ports that permit the block to be properly connected to the other ones. These ports allow the flow of entities that represent the population of the model, the Agents.
In the model described in this project work the agents represent the buses at different levels of assembly process: at the beginning the agent represent only the modules of the body structure welded together to obtain the top structure of the vehicle while at the end they stand for the whole working vehicle.
The sequence of blocks can branch and potentially assume infinite structure combinations but it generally starts with a Source block and end with a Sink one.

### 3.2.2 Blocks and commands

This chapter describes the blocks employed to build the model of the assembly line. The main libraries used are the Process Modelling and the Agent Library.
As mentioned before the model starts with a source block that generates the agents which represent buses in this project work. Since the line is designed to sustain the assembly process of three different types of buses (with different process times according to the size) the agents must not be all of the same type.
Therefore, the agent bus (called Part) contain the Parameter colour which permit this population to assume different colour:

- Red agents represent the 12 m buses
- Blue agents represent the 15 m buses
- Yellow agents represent the 10 m buses

The agents employed in this model have a 2D circular shape as visible in Figure 3.6.

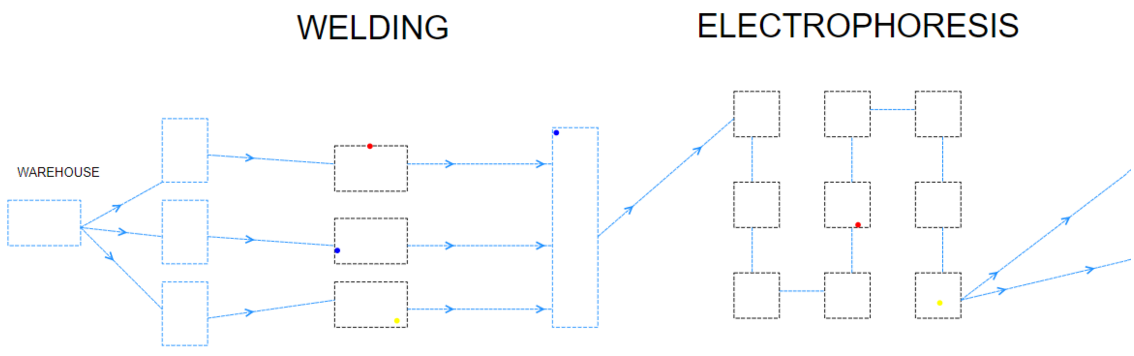



FIGURE 3.6: Agents representation

Parameters are frequently used for representing some characteristics of the modelled agents/systems in a static way; it is generally a constant in a single simulation and is changed only when the model behaviour needs to be adjusted.
AnyLogic not only supports primitive Parameter types as double, integer or Boolean but also of any Java classes.
In order to obtain three different colours agents, three different sources are required. In the following image it is possible to see the different properties of the source block that generates the 12 m long buses:

- The agents arrival timing can be set on inter arrival time or on arrival rate; the inter arrival time has been selected and it ensures that the agents (the modules to be welded in OP10) are generated every 5 h
- The number of maximum agents generated can be infinite or limited, as in the case of the simulation
- The location of arrival is referred to a specific portion of the working space that is logically connected to this block and it is called Warehouse. This is possible thanks to blocks called Space mark-ups which belong to the Process Modelling Library. The most used ones are the Nodes and the Paths. Each node can be connected with one or more paths allowing a visual representation of the agent flowing inside that specific block linked to the node.

- The exit action ensures, through a Java code string agent.color=red , that the agent exiting the source will be red.

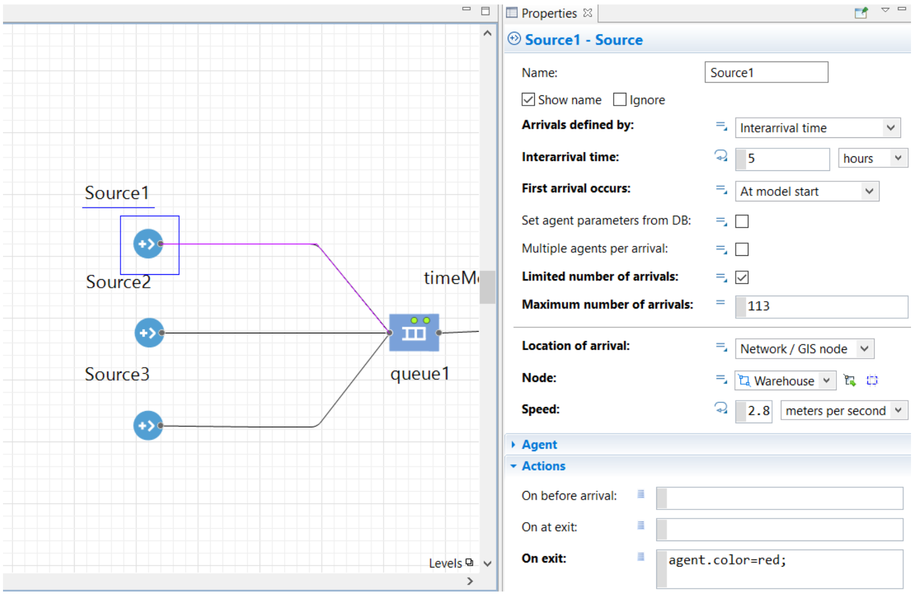



FIGURE 3.7: Source block

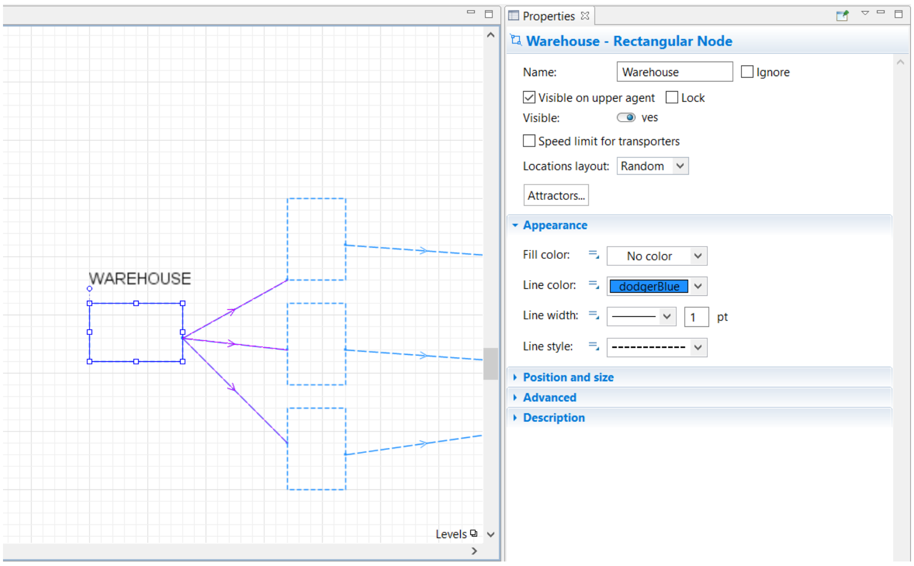



FIGURE 3.8: Space mark ups

Another important block in the model is the Queue. Several queues are placed in the line before and after the Delay blocks that simulate the operations performed

in each workstation.
The main properties to be defined in the queue block are:

- Queuing technique among FIFO, LIFO, agent based and priority based; the choice for all the queues has been the FIFO technique.

- Capacity of the queue, whose limit has not actually been set in order to analyse the effective queue length experienced by the buses in the line. This information is collected and visualized using histograms and with Presentation library blocks. The queue lengths definition, as trade-off between high throughput and the necessity to gain space in the plant is a target result of the optimization process of the line.

- Actions to be performed on enter/at exit/on exit of the agents from the block.

In particular using Java string codes on enter and on exit of the agents from the queue it is possible to store the current number of agents in the queues in order to define an optimum routing of the agents inside the line; it is fundamental to have an efficient allocation of the agents between the different branches of the line in order to obtain a balanced line and avoid overloads in some points and empty stations in other.
For example, using the strings Q1++ in the action box on enter and Q1– in the on exit box it is possible to store in the Variable called Q1 the exact number of agents present in the Queue1.
The Variables are generally used to store and collect the results of model simulation, to model some data units or object characteristics which change over time. As for Parameters, AnyLogic supports any Java classes but a Variable, differently form a Parameter, represents a dynamic model state and may change during simulation.
In our case the variable Q1 properties have to be set to host an integer number and the size of the Queue1 using the Java function Queue1.size().
The same procedure is used for the other queues and the relative variables.

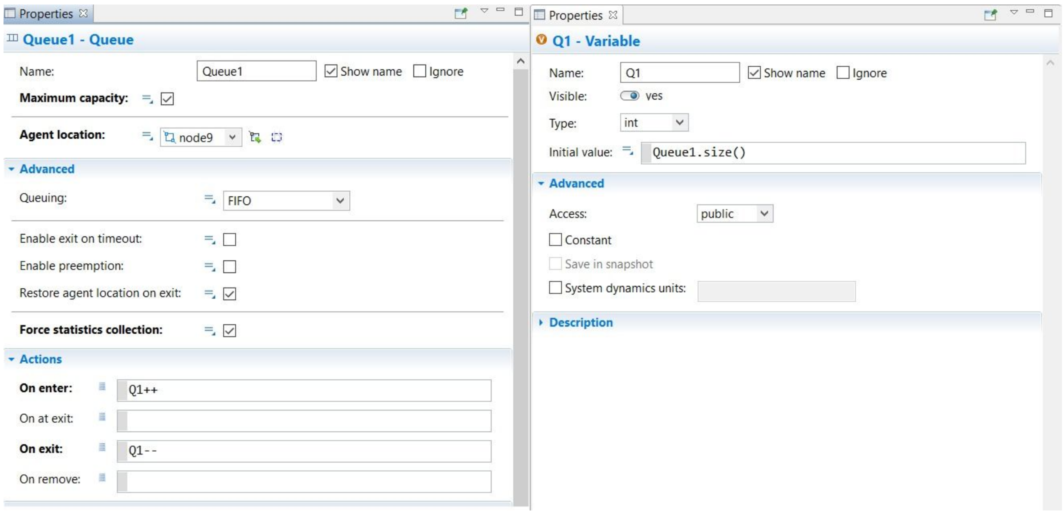



FIGURE 3.9: Queue and variable properties

Each station of the assembly line has to contain a suitable number of machines fulfilling a trade-off between three main requirements:

- Achievement of the target output
- Optimum utilization of the machines, whenever it is possible
- Reduction of queues lengths

According to these criteria each station can have potentially a different number of machines and therefore it is necessary to implement in the model a system to branch the line and efficiently route the agents; the blocks employed for this goal are the SelectInput and SelectOutput.

These blocks only have a logical connection between them and the criterion used to route the agents from one SelectInput to several SelectOutput blocks is given by a Function block.

As it is evident from the following image the function used in this model is characterized by a Function Body which define the behaviour of agents flowing in the block connected to this function. For a correct definition of the function it is necessary to specify the arguments of the Java code in the body, in terms of name and type agents.

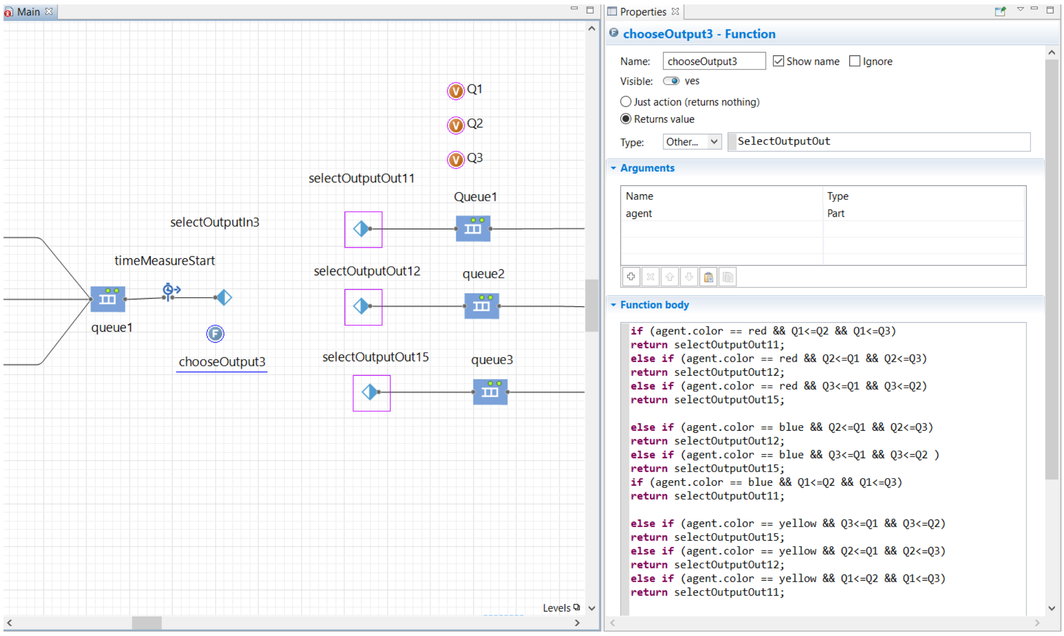



FIGURE 3.10: SelectOutput and Input block

In our case the function body is composed by several conditional statements (if, else if) that compare 2 conditions in order to select the proper line branch:

- The bus length (agent colour)
- Size of the queues stored in the Variables

So the model works giving priority to certain branches according to the bus size, for example in the image above it is possible to see that the sequence for the chosen output for the 12 m long bus (red agent) is the top branch then the one in the middle and finally the lower one. The lines are thus prioritized as it happens in a real case without devoting a line exclusively to a certain type of product.
In fact, each bus has the possibility to be located in other line branches if the queue size ahead of the line branch originally devoted to that particular bus length is higher with respect to other line branches.
The combination of these two conditions allow to have an efficient allocation of agents in the line.
Another key aspect of the model is the necessity to simulate the activity operations inside the stations; the block devoted to this goal is the Delay.
This block delays the exit of the agent simulating the time spent by the bus in the

line for the completion of the specific activity.
As the Queue, it can be visualized using Space Mark-ups and the delay time can be set using a Function. It is very useful in this case to define a function since in this way it possible in a single action to define different delays for different bus lengths simulating the real case of increment or reduction of assembly time due to the different size of the products.
Finally, it is worth to speak about the timeMeasureStart and timeMeasureEnd blocks.
As their name suggest, they are used to start and to end counting the simulation time as the agents pass through them.In Figure 3.12 they are visible together with the Sink block which represent the very end of the line model.

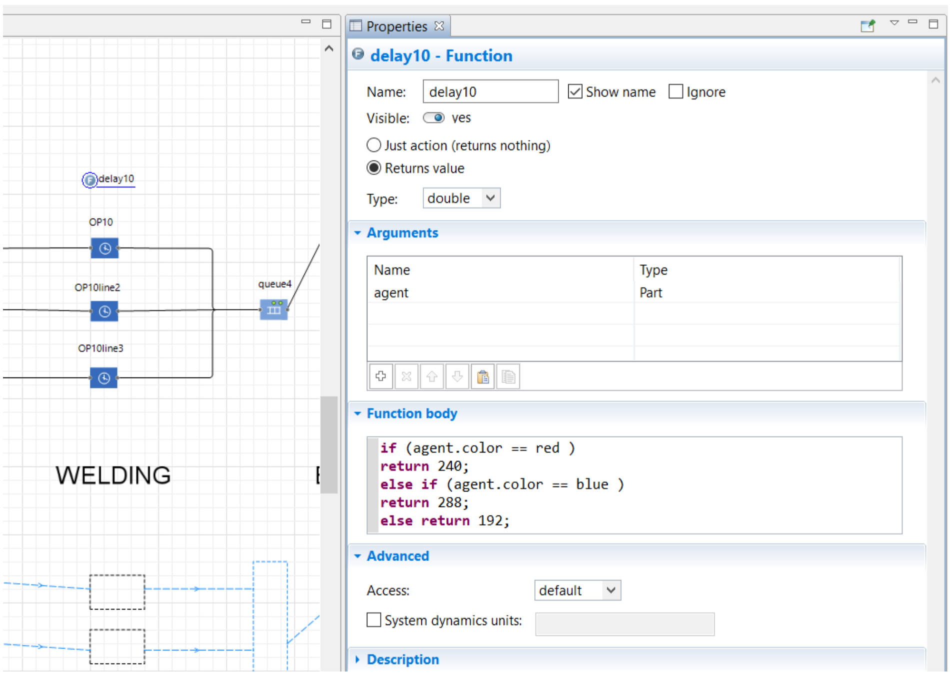



FIGURE 3.11: Delay block

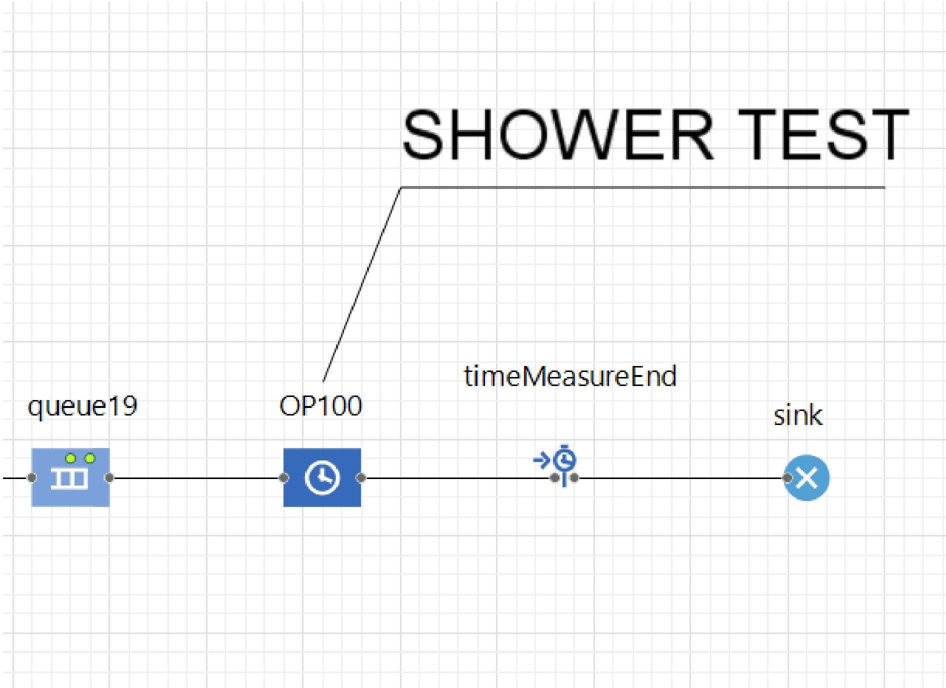



FIGURE 3.12: Sink block

### 3.2.3 Assembly line structure

The line structure follows the 10 stations assembly process described in the previous chapter.
The starting assumption for the software implementation is the selection of the number of parallel machines m for each workstation m = 1.
After this initial choice, a series of simulations using different line structures have been performed and the process parameters are analysed and exploited to implement changes in the line structure.
This approach lead to a cyclic process of optimization which could be possible only in a virtual environment as the software modelling one.
The main line performances indices that used to optimize the assembly process are:

- Line Output
- Parallel machines utilizations
- Bottlenecks

- Buffers

This Chapter describes the performances of the obtained line structure.
Actually, this is only a starting point for the final optimization process of the line structure since the point of view adopted so far is the deterministic one.
In fact, the line structure optimization will be again object of discussion starting from Chapter 4 where a stochastic approach to the definition of process times will be introduced, bringing the model closer to a real system.
The line starts with the assembly process of the 6 modules necessary to compose the body structure of the bus; they are modelled by a single agent generated in the right before the first station and moved to a first queue1.
Then each agent is routed into one of the 2 parallel machines that compose the body assembly station (OP10) passing through 2 different sub stations: 1 for the modules assembly and 1 for the quality inspection.
The inter arrival rate for the modules is $T_a$=6 h/pz thus the arrival rate $r_a$=1/$T_a$= 0,167 pz/h.
The agents flowing outside this station (which now represent the whole body structure) are collected into a single queue and go inside the electrophoresis treatment station (OP20). In this station they undergo several chemical treatments passing through 9 different sub stations; due to costs reasons this station is made up by only 1 machine.
After passing into another queue, the agents are routed into the panels fixing station (OP30) composed of 2 parallel machines and 2 sub stations for each machine: the panels are first stretched and glued on the buses body structure and then the frame structure for windows is placed.
The bodies then pass through the first painting station (OP40) composed of only 1 machine; this station is composed of 3 sub stations to perform cleaning, application of primer coat and drying.
The agents (now representing the painted body structure) are moved to the body drop station (OP50) where the body is welded and jointed on the underbody of the vehicle.
This station is composed of 2 parallel machines and 5 sub stations. The buses (which now theoretically can be even turned on due to the connection of electrical wires, engine, steering system and other mechanical components) are routed to the interiors finishing station (OP60) where several components and equipment are installed, as for example electrical wiring, lighting, air conditioning system,

interior panelling, seats and windows.
This station is composed of 3 parallel machines and 6 sub stations.
The buses fully working and with all internal trim and equipment are moved to the second painting station (OP70) where they receive a styling painting and it is made up of 2 parallel machines and 3 sub stations for the application of top coat, the drying process and the vinyl stickers application.
In the end the buses go through the final three stations where undergo the final tests: brake (OP80), driving (OP90) and shower (OP100) tests.
Each of these stations are composed of 1 machine with queues between them.
The final number of parallel machines m, chosen for each station, are reported in Table 3.1.

TABLE 3.1: Number of parallel machines for each station

| Station | m |
|---|---|
| ASSEMBLY OF BODY STRUCTURE | 2 |
| ELECTROPHORESIS TREATMENT | 1 |
| PANELS FIXING | 2 |
| COAT PAINTING | 1 |
| BODY DROP | 2 |
| INTERIORS/FINISHING | 3 |
| STYLE PAINTING | 2 |
| BRAKE TEST | 1 |
| DRIVING TEST | 1 |
| SHOWER TEST | 1 |

### 3.2.4 Balancing and performance analysis

The main line performances indices analysed and monitored in order to optimize the assembly process are:

- Line output
- Parallel machines utilization

- Bottleneck station
- Buffers

The simulation is carried to model the line assembly process of a whole year. As a start, the whole yearly production time is divided into 2 main periods:

- 130 days devoted to working shift A
- 130 days devoted to working shift B

This is only an initial choice made to offer flexibility according to the target production value that can be different from 780 buses/year. In fact, by selecting the proper number of days, it is virtually possible to adjust the production rate according to the market demand.
The duration of each simulation has therefore set to 2470 h which is the result of 130 days spent working with only 1 shift of 7.5 h and 130 days with 1.5 shift of 11.5 h (total 260 working days/year).
The line performance indices are computed using built in AnyLogic tools and specific blocks.
The output is computed in AnyLogic counting the number of agents going into the Sink block during the simulation.
The value of the Sink, collected using a Java code string sink.count() is then displayed using Analysis library blocks as the Bar Chart; a similar procedure is applied to show the number of generated agents in the system by the Source block and the number of works in progress elements (WIP).

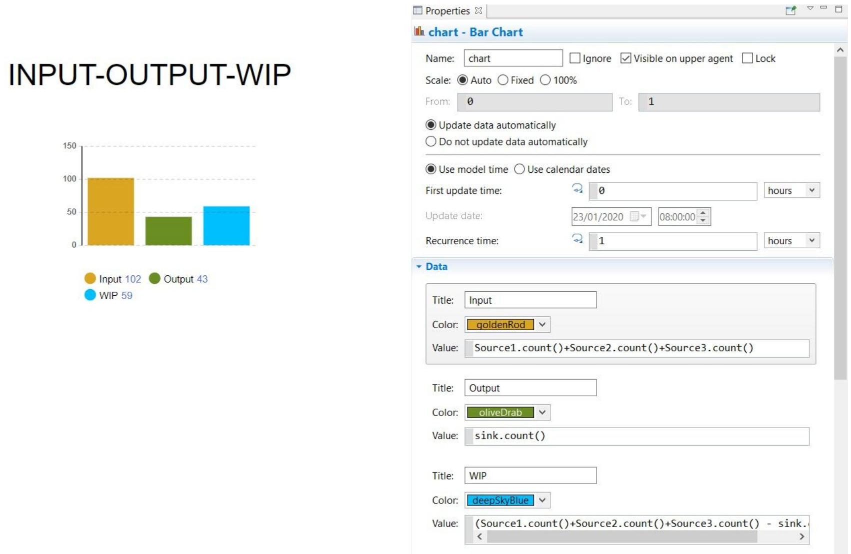



FIGURE 3.13: Input, Output and WIP

For what concerns the machines utilizations, they are computed using Java string codes as OP10.statsUtilization.mean() which return, in this case, the average utilization of the machine of the first line of OP10. The values are then displayed using a Bar Chart.
In the end, for what concerns the queues sizes, their maximum dimensions during the simulation is computed by the software as the previous quantities and their value can be shown using a Bar Chart block.
They have been collected exploiting the Statistics section of AnyLogic which keeps trace of important production parameters. The computation of the buffers is of primary importance in a plant that produces bulky products as a bus.

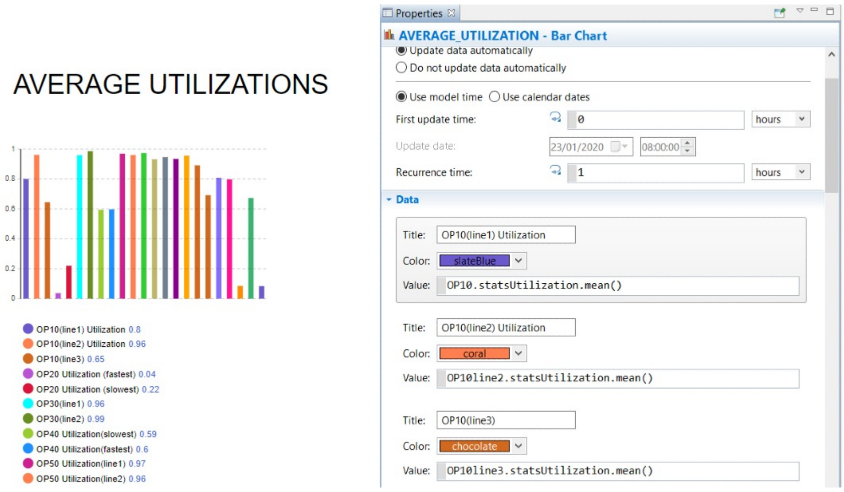



FIGURE 3.14: Utilization

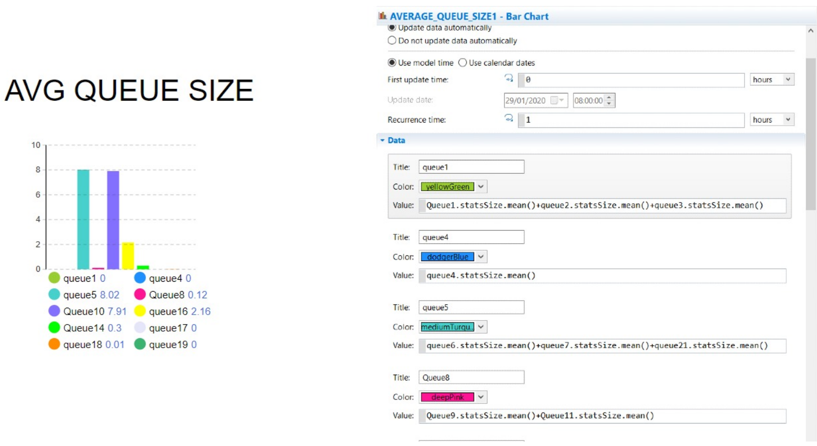



FIGURE 3.15: Queue

The choice of the number of parallel machines m for each workstation is the results of the optimization of the parameters described before; this process is called line balancing since aims at allocating efficiently the workload among all the stations.

The value of m has thus been chosen as a trade-off between:

- Efficient workstation utilization
- Reduced queues in the plant

An increase in m allows to reduce buffers but reducing the utilization of each parallel machine, while a reduced m could prevent the possibility to reach the target and create high queues in the line. The machine utilization have been collected in Table 3.2
In particular, for each station, only the substation with the highest utilization have been reported; they represent the bottleneck in that specific workstation and they give information about the possibility to further reduce the number of parallel machines.
Furthermore, the utilization of the single machine stations has been omitted; in fact, even if the utilization can be low, these machines are of course required for the completion of the assembly process.

TABLE 3.2: Parallel machines utilization

| **Mix 1** | | **Mix 2** | | **Mix 3** | |
|---|---|---|---|---|---|
| OP11(Line1) | 91,9% | OP11(Line1) | 89,6% | OP11(Line1) | 95,6% |
| OP11(Line2) | 91,9% | OP11(Line2) | 89,6% | OP11(Line2) | 95,6% |
| OP31(Line1) | 62,6% | OP31(Line1) | 66,2% | OP31(Line1) | 73,2% |
| OP31(Line2) | 43,9% | OP31(Line2) | 44,7% | OP31(Line2) | 56,1% |
| OP51(Line1) | 86,8% | OP51(Line1) | 85,1% | OP51(Line1) | 86,8% |
| OP51(Line2) | 91,7% | OP51(Line2) | 89,0% | OP51(Line2) | 95,5% |
| OP65(Line1) | 85,7% | OP65(Line1) | 80,4% | OP65(Line1) | 84,5% |
| OP65(Line2) | 89,4% | OP65(Line2) | 86,1% | OP65(Line2) | 91,0% |
| OP65(Line3) | 54,0% | OP65(Line3) | 69,6% | OP65(Line3) | 59,0% |
| OP73(Line1) | 75,3% | OP73(Line1) | 76,3% | OP73(Line1) | 64,1% |
| OP73(Line2) | 56,2% | OP73(Line2) | 61,2% | OP73(Line2) | 68,1% |

The different product mixes leads to slightly different utilization due to the bus sizes: mix 2 and mix 3 represent respectively the one with the highest and the lowest machine utilization.
Besides, due to the different priority assigned to each line according to the bus size there are lines with higher or lower u with respect the different product mix; for example, in OP65 line1 has the highest u in mix 1, line 2 the highest in mix 2 and line 3 for mix 3.

The optimum utilization range has been considered from 85% to 97% which provide the machine to be employed for a suitable quantity of time without being so close to the critical value of 1.
There are also some machines whose utilization are below this optimum range:

- OP30
- OP60
- OP70

For all these stations it is not possible to further reduce m unless we accept the possibility of having very high queues in the line,as visible in Figure 3.16.
In fact, independently simulating a reduction of 1 machine for each of the previous mentioned station the number of agents waiting in the queues is:

- 58 before OP30
- 28 before OP60
- 77 before OP70

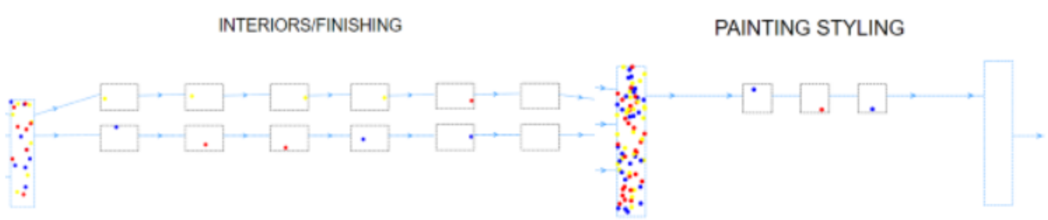



FIGURE 3.16: Example of queues with a further reduction of m

These buffer dimensions are not acceptable and therefore this reduction is discarded.
It is possible to see that the buffers are optimized inside the line with the exception of the queues before OP10 and OP90.

TABLE 3.3: Max number of agents waiting in each buffer

| Station | Agents |
|---|---|
| OP20 | 1 |
| OP30 | 2 |
| OP40 | 2 |
| OP50 | 2 |
| OP60 | 3 |
| OP70 | 2 |
| OP80 | 1 |
| OP90 | 40 |
| OP100 | 0 |

For what concerns O10, the agents in the queues refer to the modules that have to be stored in the warehouse before entering in the line, while for OP90 the agents stand for the fully working vehicle which can be parked outside waiting for the drive test.
In both cases these chosen solution is feasible and does not affect the space requirements inside the line.
The statistics section of the model employed so far are visible below.


FIGURE 3.17: Software statistics bar charts

In order to conclude this analysis about the line performance it is important to evaluate the bottleneck station of the line and its production rate $r_b$.
The production rate is computed as:

$$r_b = \frac{m}{T_0} \tag{3.1}$$

And in the case of the station with the highest utilization $r_0 = r_b$.
This is station OP11 and it is possible to conclude that $r_b$ = 0,570 pz/h (value obtained for the product mix 1).
Since it is the first station of the line, is it crucial that the inter arrival rate of modules coming from the warehouse is properly chosen to guarantee a correct utilization of OP10 and that its functionalities are always preserved in order to prevent delays on the whole line.
Together with OP11 also OP90 represents a crucial station in terms of production rate but its impact on the productivity of the line is marginal since it is placed at the end of the process.
As it was predictable, the highest queues are placed before the stations with the lower production rates.
It is possible to conclude that the chosen layout offers good results in terms of utilization, buffers and it also reaches the target output of 780 buses/year, for all the 3 product mixes.

## 3.3 Internal benchmarking

### 3.3.1 Description

The performance parameters presented before are useful to compare the line performances with expected targets or even with other different lines; this activity is called external benchmarking.
Actually, it is important to establish if the line still has margins of improvement comparing the measured performances to theoretical ones; this is called internal benchmarking.
This activity is based on the definition of 3 different theoretical working conditions:

- The best case, BC
- The worst case, WC
- The practical worst case, PWC

The best case occurs in the case of no variability, the worst case whenever there is the largest deterministic variability and the practical worst case in the situation of largest random variability. These 3 cases are modelled using the formulas below, which shows the variation of TH and CT in function of the independent variable WIP.

- Best case

$$TH = \frac{w}{T_0} \qquad if\ \ w \leq W_0 \tag{3.2}$$

$$TH = r_b \qquad if\ \ w > W_0 \tag{3.3}$$

$$CT = T_0 \qquad if\ \ w \leq W_0 \tag{3.4}$$

$$CT = \frac{w}{r_b} \qquad if\ \ w > W_0 \tag{3.5}$$

- Worst case

$$TH = \frac{1}{T_0} \tag{3.6}$$

$$CT = w \cdot T_0 \tag{3.7}$$

- Practical worst case

$$TH = \frac{w}{W_0 + w - 1} r_0 \tag{3.8}$$

$$CT = T_0 + \frac{w - 1}{r_b} \tag{3.9}$$

Where:

- $r_b$ is the bottleneck rate
- $W_0$ is the critical WIP

- $T_0$ is the raw process time

The 3 working conditions identify two different areas in the plots TH/WIP and CT/WIP:

- a Good area, between PWC and BC
- a Bad area, between PWC and WC

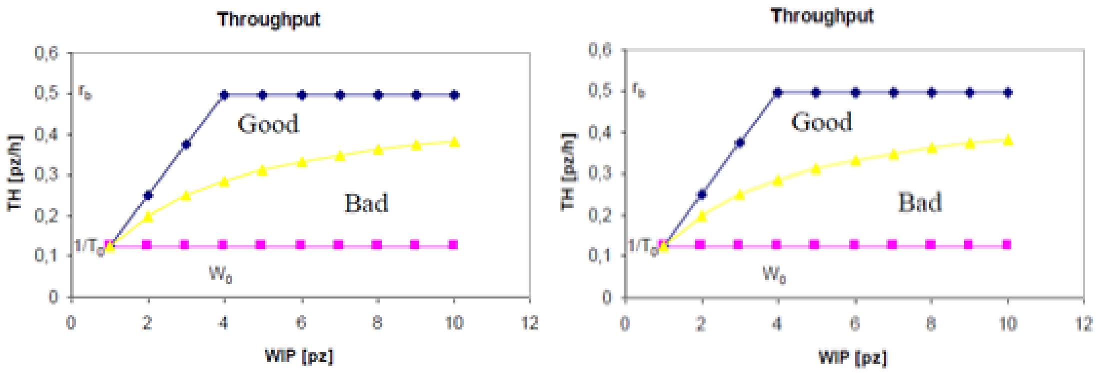



FIGURE 3.18: Good and Bad areas

The Good area represents an optimum working zone for the line while the Bad one is an area of possible improvement.
Therefore, these plots are useful to understand if the process should be optimized or not by visually analysing the working conditions.

### 3.3.2 Application

TH and CT are evaluated for 4 different values of the WIP with respect the critical one:

- w = $W_0$
- w = $\frac{3}{2}W_0$
- w = $2W_0$
- w = $\frac{5}{2}W_0$

with the following line parameters (product mix 1) :

- $u_{MAX}$ = 0,919
- $r_b$ = 0,570 pz/h
- $T_0$ = 45 h
- $W_0 = r_b \cdot T_0$ = 25,65 pz

Results are visible in the images below.

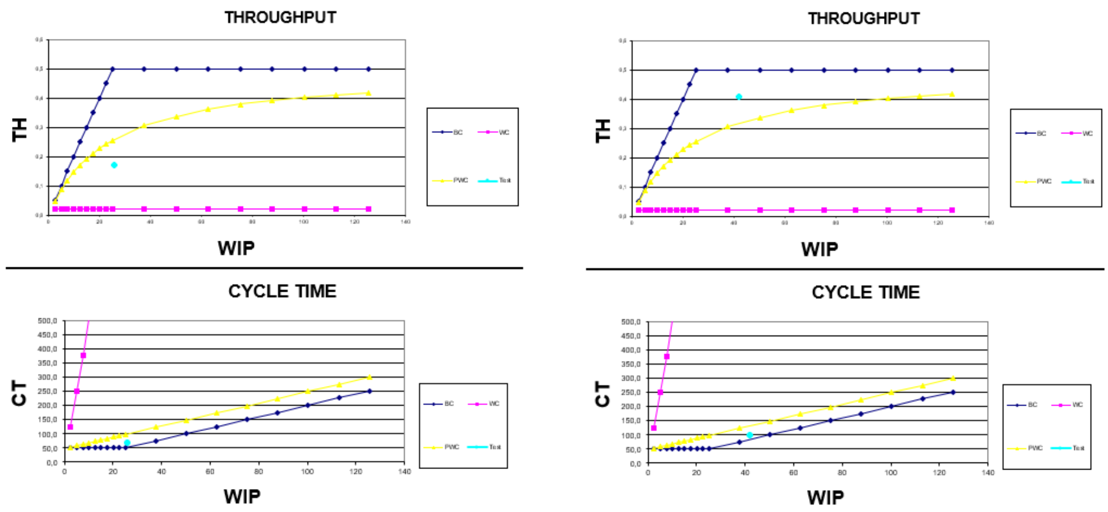



FIGURE 3.19: w = $W_0$ and w = $\frac{3}{2}W_0$

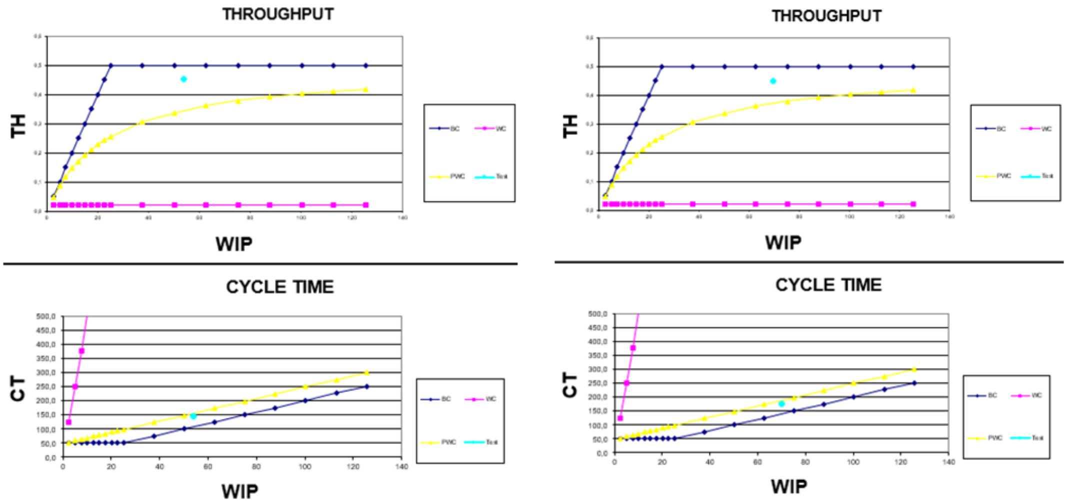



FIGURE 3.20: w = $2W_0$ and w = $\frac{5}{2}W_0$

Looking at the plots it is possible to see that the line performance improves as long as the WIP increases, in particular for what concerns the TH.
In fact, the throughput is in the Bad area during the first hours of simulation since the agents are still flowing in all the stations, with a quite low level of throughput. As long as the process goes on the TH increases until becoming constant, shifting the working conditions point to the Good area.
Since the effect of this transient condition is present only at the beginning of production, it is possible to conclude saying that the overall line performances already fall in an optimum range without the necessity for further improvements.

# Chapter 4

# Model update

## 4.1 Stochastic time analysis

### 4.1.1 Variability sources

The time analysis performed in Chapter 6 is based on a deterministic approach to the problem: the duration of the assembly process is always the same with no variations from simulation to simulation.
In order to have a model whose behaviour is closer to a real situation it is fundamental to consider the natural variability phenomena that can affect the duration of each task, as for example the different levels of skill among the workers, the quality changes from product to product, the material differences etc.
Furthermore, no additional sources of variability like failures, reworking activities and setups are taken into account; for all these reasons a stochastic approach to the problem has to be developed and the model should be redesigned according to new specifications.
In particular the new model works using as input values probability distributions properly designed to take into consideration the variability phenomena described before.
The probability distributions employed are:

- Normal
- Exponential

At the beginning the average process time of each workstation is corrected in order to model the natural variability phenomena, then the failures of the machines, setups and in the end to take into considerations the possibility of reworking activities; the obtained values are the effective times.

These sources of variability are called detractors since, as a results of their presence inside the model, the process time increases.


FIGURE 4.1: Variability composition

### 4.1.2 Probability distributions

The Normal (Gaussian) distribution is an unbounded continuous distribution with a symmetric bell shape and it is the one of the most important probability distribution in statistics.
One of the main reasons is due to the Central Limit Theorem (CLT): this theorem states that if we add a large number of random variables, the distribution of the sum will be approximately normal under certain conditions. The importance of this result comes from the fact that many random variables in real life can be expressed as the sum of a large number of random variables and, by the CLT, we can argue that distribution of the sum should be normal.
Because of its property this distribution gives the possibility of modelling a large number of phenomena and thus it finds many applications in statistics.
This distribution is characterized by 2 parameters:

- the mean value $\mu$, which defines the horizontal shift of the distribution
- the standard deviation $\sigma$, which is the shape parameter

The probability density function of this distribution is:

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{\frac{-(x-\mu)^2}{2\sigma^2}} \tag{4.1}$$

The Normal distribution is frequently used to represent symmetrical data but it suffers from being unbounded in both directions: in our case, for example, it

is very unlikely that an actual process time for a workstation would be lower of the average value. That is why for the purpose of this project work also the Exponential distribution is analysed.
The Exponential distribution is frequently used to represent the time between random occurrences such as the time between arrivals at a specific location in a queuing model, the time between failures in reliability models or the services times of a specific operation.
This distribution is a continuous and bounded on the lower side; it starts at a finite minimum value and it continuously decreases for increasing values of the random variable x.
Differently from the Normal distribution, it is characterized by only 1 parameter $\lambda$ which gives different shapes to the curve. In fact, it is possible to demonstrate that:

$$\mu = \sigma = \frac{1}{\lambda} \tag{4.2}$$

The probability density function of this distribution is:

$$P(x) = \lambda e^{-\lambda x} \qquad x > 0 \tag{4.3}$$

One of the main features of this distribution is the memoryless property.
This property refers to the cases when the distribution of a "waiting time" until a certain event, does not depend on how much time has already elapsed.
Therefore, to model memoryless situations we must not consider in which state the system is in, since the probability that that the state will change is not influenced by the history of the process.

### 4.1.3 Detractors modelling

Each source of variability can be modelled by a probabilistic distribution and be defined by its coefficient of variation c.
The coefficient of variation is an adimensional quantity which defines the level of variability of the stochastic variable belonging to a particular distribution:

- c < 0,75 low variability
- 0,75 < c < 1,33 medium variability

- c > 1,33 high variability

and its relationship with the mean value and the standard deviation of the distribution is:

$$c = \frac{\sigma}{\mu} \tag{4.4}$$

Starting from the natural variability, a low level of variability has been selected and thus the natural coefficient of variation $c_0$ has been chosen equal to 0,75. Therefore, the standard deviation is:

$$\sigma_0 = c_0 \cdot \mu_0 \tag{4.5}$$

where $\mu_0$ represents the average times presented in Chapter 3: this is the first step to pass from a deterministic approach to a stochastic one, shifting from average times to a distribution of times.
The following source of variability is the one related to failures; three parameters have to be selected for each workstation:

- mean time to failure $m_F$
- mean time to repair $m_R$
- coefficient of variation of the distribution of repairs $c_r$

The first two quantities define the availability of the machine in the workstation:

$$A = \frac{m_F}{m_F + m_R} \tag{4.6}$$

and their value have been chosen for each station:

- $m_F$=30 [h] and $m_R$=1 [h] for OP 10, OP30, OP50, OP60, OP80, OP90, OP100
- $m_F$=150 [h] and $m_R$=5 [h] for OP20, OP40 and OP70

It is in fact less frequent that a failure occurs in the electrophoresis treatment and painting stations but in the case of failure the repair time is higher due to the complexity of the equipment.
The coefficient of variation of the distribution of repairs $c_r$ has been selected equal to 1 to model a case of medium variability.

Taking into account the previous quantities we obtain the process time $t_{eg}$ and the variance $\sigma_{eg}^2$ of the distribution that also takes into account failures:

$$t_{eg} = \frac{\mu_0}{A} \tag{4.7}$$

$$\sigma_{eg}^2 = \frac{\sigma_0^2}{A^2} + \frac{({m_R}^2 + {\sigma_r}^2)(1-A)\mu_0}{A m_R} \tag{4.8}$$

where $\sigma_r$= $c_r \cdot m_r$ and $c_r$ = 1 for a medium variability level.
To consider the effect of tool changes and setups we define the mean number of parts manufactured between two setups $N_s$, the mean setup time $t_s$ and the coefficient of variation of the setups distribution $c_s$. The value chose for these quantities are:

- $N_s$ = 20 [pz] and $t_s$ = 0,25 [h] for OP10, OP30, OP50, OP60, OP80, OP90, OP100
- $N_s$ = 50 [pz] and $t_s$=1 [h] for OP20, OP40 and OP70
- $c_s$ = 1 to have a medium level of variability

The expression of the effective process time $t_{es}$ and the effective process standard deviation $\sigma_{es}$ also modelling the setups are:

$$t_{es} = t_{eg} + \frac{t_s}{N_s} \tag{4.9}$$

$$\sigma_{es} = \sigma_{eg}^2 + \frac{\sigma_s^2}{N_s} + \frac{(N_s - 1)\, t_s^2}{N_s^2} \tag{4.10}$$

Finally, we introduce the reworking probability p in order to obtain the final expressions of the effective process time $t_{eff}$ and the standard deviation $\sigma_{eff}$ taking into account also the reworking process.
The quantity p has been evaluated as following:

- p = 0,05 for OP10, OP30, OP50, OP60, OP70, OP80, OP90, OP100
- p = 0,02 for OP20, OP40, OP70

This choice is due to the higher reliability of the equipment and standardization of activities employed to perform the operations in OP20, OP40 and OP70 with respect the rest of the assembly line. The results of the combination of these detractors are the effective process time $t_{eff}$ and the standard deviation $\sigma_{eff}$ that define a distribution of times in which natural variability, reworking, failures and setup are all taken into account. Their final expressions are:

$$t_{eff} = \frac{t_{es}}{(1-p)} \tag{4.11}$$

$$\sigma_{eff} = \sqrt{\frac{\sigma_{es}^2}{(1-p)} + \frac{p \cdot t_{es}^2}{(1-p)^2}} \tag{4.12}$$

The obtained values are reported in Table 4.1.
The total Raw Process time is 50,17 h.
As it is possible to see from the tables, the value of the effective standard deviation is not negligible with respect the effective time value; this is due choice of the detractors values.
The result is a slightly overall conservative analysis which has considered more suitable in this design phase; a further refinement is desirable with additional information about the specific technology employed in the assembly process and the workforce.

TABLE 4.1: Values for 12 m bus

| Stations | $t_{eff}$ [h] | $\sigma_{eff}$ [h] | Stations | $t_{eff}$ [h] | $\sigma_{eff}$ [h] |
|---|---|---|---|---|---|
| OP11 | 4,001 | 3,093 | OP52 | 3,276 | 2,538 |
| OP12 | 0,376 | 0,327 | OP53 | 2,189 | 1,707 |
| OP21 | 0,362 | 0,441 | OP54 | 2,189 | 1,707 |
| OP22 | 0,362 | 0,441 | OP55 | 0,376 | 0,327 |
| OP23 | 0,098 | 0,207 | OP61 | 2,189 | 1,707 |
| OP24 | 0,274 | 0,367 | OP62 | 1,101 | 0,877 |
| OP25 | 0,186 | 0,291 | OP63 | 3,276 | 2,538 |
| OP26 | 0,098 | 0,207 | OP64 | 0,557 | 0,464 |
| OP27 | 0,098 | 0,207 | OP65 | 4,364 | 3,370 |
| OP28 | 0.537 | 0,582 | OP66 | 2189 | 1,707 |
| OP29 | 0.537 | 0.582 | OP71 | 2,186 | 1,865 |
| OP31 | 2,189 | 1,707 | OP72 | 2,186 | 1,865 |
| OP32 | 2,189 | 1,707 | OP73 | 2,549 | 2,144 |
| OP41 | 1,370 | 1,237 | OP80 | 0,285 | 0,260 |
| OP42 | 1,370 | 1,237 | OP90 | 2,189 | 1,707 |
| OP43 | 1,461 | 1,307 | OP100 | 0,285 | 0,260 |
| OP51 | 3,276 | 2,538 | | | |

The obtained values of the effective process times take into consideration the 4 sources of variability but they are referred to a single product, in particular the 12 m long bus.
The process time of the other two products are obtained increasing or decreasing of 20% the $t_{eff}$ of the 12 m bus and are summarized in Table 4.2
The assembly steps whose duration is not affected by bus size has been kept equal.

TABLE 4.2: Values of $t_{eff}$ [h] for 10 and 15 m buses

| 15 m (+20%) | | 10 m (-20%) | |
|---|---|---|---|
| OP11 | 4,802 | OP11 | 3,201 |
| OP12 | 0,376 | OP12 | 0,375 |
| OP21 | 0,362 | OP21 | 0,362 |
| OP22 | 0,362 | OP22 | 0,362 |
| OP23 | 0,098 | OP23 | 0,098 |
| OP24 | 0,274 | OP24 | 0,274 |
| OP25 | 0,186 | OP25 | 0,186 |
| OP26 | 0,098 | OP26 | 0,098 |
| OP27 | 0,098 | OP27 | 0,098 |
| OP28 | 0,537 | OP28 | 0,500 |
| OP29 | 0,537 | OP29 | 0,500 |
| OP31 | 2,626 | OP31 | 1,751 |
| OP32 | 2,626 | OP32 | 1,751 |
| OP41 | 1,644 | OP41 | 1,096 |
| OP42 | 1,644 | OP42 | 1,096 |
| OP43 | 1,753 | OP43 | 1,169 |
| OP51 | 3,932 | OP51 | 2,621 |
| OP52 | 3,932 | OP52 | 2,621 |
| OP53 | 2,626 | OP53 | 1,751 |
| OP54 | 2,626 | OP54 | 1,751 |
| OP55 | 0,376 | OP55 | 0,376 |
| OP61 | 2,626 | OP61 | 1,751 |
| OP62 | 1,321 | OP62 | 0.881 |
| OP63 | 3,932 | OP63 | 2,621 |
| OP64 | 0,668 | OP64 | 0,446 |
| OP65 | 5,237 | OP65 | 3,491 |
| OP66 | 2,626 | OP66 | 1,751 |
| OP71 | 2,623 | OP71 | 1,749 |
| OP72 | 2,623 | OP72 | 1,749 |
| OP73 | 3,058 | OP73 | 2,039 |
| OP80 | 0,285 | OP80 | 0,285 |
| OP90 | 2,189 | OP90 | 2,189 |
| OP100 | 0,285 | OP100 | 0,285 |
| Raw Process Time | 58,99 [h] | Raw Process Time | 41,35 [h] |

## 4.2 New line structure

### 4.2.1 Balancing and performance analysis

The results of the previous chapter have been used as parameters to design the distribution of times that become the new input time data of the software.
In particular, the simulations are carried one using both the Normal and the Exponential distributions that are built as follows:

- Normal distribution : $\mu = t_{eff}$ and $\sigma = \sigma_{eff}$
- Exponential distribution: $\lambda = 1/t_{eff}$ and finite minimum value = $\mu_0$ which represents the average deterministic values. In this way the resulting distribution will take into consideration that $\mu_0$ are the time durations that more likely will occur but with the (decreasing) possibility to have much higher duration with a mean value = $t_{eff}$.

In order to implement the probability distributions in AnyLogic all the Delay blocks properties have been changed.
In particular, the Delay has been modified to read the output of a Function which generates the probability distribution, properly changing the parameters according to the size of the buses.
The two Java strings codes used in the Function to obtain the distributions are:

- normal(mean, standard deviation)
- exponential(lambda , min)

In Figure 4.2 the function structures used for OP10 are shown.

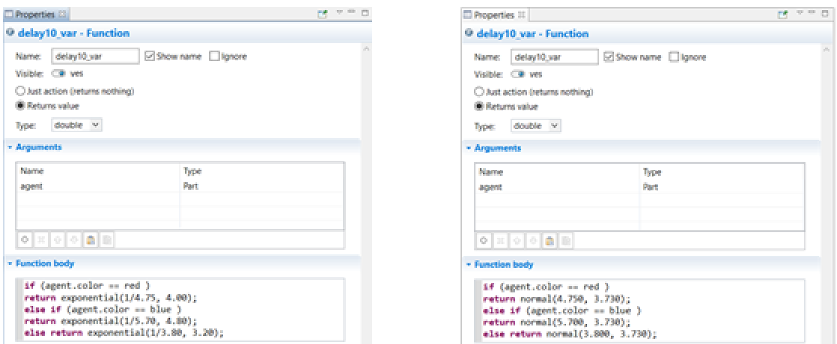



FIGURE 4.2: Delay function body

Both the distributions have been implemented using AnyLogic and the line structure has been modified to reach the target output of 3 buses/day due to the additional amount of time required. In particular, the Exponential distribution results have a higher impact on the duration of the process and therefore it has been chosen as the reference distribution for the optimization process.
Starting from the final considerations about the utilizations and buffers evaluated in the deterministic approach, it is already possible to know in which workstations it is necessary to start increasing the number of parallel machines m.
Therefore m has been increased first for OP10 (bottleneck station) and later for OP50 and OP60, where the higher utilizations have been registered. In a cyclic process of simulation and monitoring of line performance the layout has been changed in order to find again an optimum structure using trade-off between machines utilizations, buffers and target output.
The increase of m has not only interested the stations with the highest utilizations but also several other ones, as visible in Table 4.3

TABLE 4.3: Number of parallel machines

| Stations | Previous m | New m |
|---|---|---|
| ASSEMBLY OF BODY STRUCTURE | 2 | 3 |
| ELECTROPHORESIS TREATMENT | 1 | 1 |
| PANELS FIXING | 2 | 3 |
| COAT PAINTING | 1 | 2 |
| BODY DROP | 2 | 4 |
| INTERIORS/FINISHING | 3 | 4 |
| STYLE PAINTING | 2 | 3 |
| BRAKE TEST | 1 | 1 |
| DRIVING TEST | 1 | 2 |
| SHOWER TEST | 1 | 1 |

The achieved configuration provides a throughput higher than the target one for all the three product mixes. The results are showed in Table 4.4

TABLE 4.4: Output variation at different simulation times

| | Output [buses] | Time [h] | Time [days] |
|---|---|---|---|
| MIX 1 | 780 | 2350 | 248 |
| MIX 2 | 780 | 2450 | 258 |
| MIX 3 | 780 | 2250 | 237 |

The considerations performed so far are related to reach a fixed number of assembled buses (780) with a simulation time (2470 h) based on 260 working days/year as:

- 130 days devoted to 1.5 daily working shifts (Case A)
- 130 days devoted to 1 daily working shift (Case B)

Changing the amount of time devoted for each shift case the yearly output and related throughput change too.
In the Table 4.5 is possible to see an example of this variation for the product mix 1; as long as the simulation time increases the TH increases too as a result of the reduced impact of the transient effect at the beginning of the process.

TABLE 4.5: Output variation at different simulation times

| Case A / Case B [% of days] | Working h/year | Buses/year | Buses/day |
|---|---|---|---|
| 50/50 | 2470 | 913 | 3.511 |
| 70/30 | 2678 | 951 | 3.658 |
| 30/70 | 2262 | 797 | 3.065 |

The utilization of the workstation composed of parallel machines have been computed and presented in Table 4.6.
As occurred in the deterministic case, some machines work with values of utilization outside the optimum range ; once again this configuration is due to the necessity of reducing the queues sizes inside the line.

TABLE 4.6: Parallel machines utilization after model update

| Mix 1 | | Mix 2 | | Mix 3 | |
|---|---|---|---|---|---|
| OP11(Line1) | 91,9% | OP11(Line1) | 85,5% | OP11(Line1) | 96,5% |
| OP11(Line2) | 93,1% | OP11(Line2) | 86,2% | OP11(Line2) | 96,1% |
| OP11(Line3) | 93,1% | OP11(Line3) | 85,1% | OP11(Line3) | 96,5% |
| OP31(Line1) | 73,5% | OP31(Line1) | 59,1% | OP31(Line1) | 59,8% |
| OP31(Line2) | 73,0% | OP31(Line2) | 66,5% | OP31(Line2) | 84,8% |
| OP31(Line3) | 57,2% | OP31(Line3) | 64,2% | OP31(Line) | 63,4% |
| OP41(Line1) | 86,5% | OP41(Line1) | 80,5% | OP41(Line1) | 88,1% |
| OP41(Line2) | 55,8% | OP41(Line2) | 50,7% | OP41(Line2) | 57,4% |
| OP51(Line1) | 87,7% | OP51(Line1) | 83,8% | OP51(Line1) | 86,8% |
| OP51(Line2) | 85,6% | OP51(Line2) | 86,4% | OP51(Line2) | 94,3% |
| OP51(Line3) | 86,6% | OP51(Line3) | 89,2% | OP51(Line3) | 85,7% |
| OP51(Line4) | 49,5% | OP51(Line4) | 49,2% | OP51(Line4) | 51,4% |
| OP65(Line1) | 93,0% | OP65(Line1) | 92,0% | OP65(Line1) | 87,1% |
| OP65(Line2) | 89,6% | OP65(Line2) | 85,0% | OP65(Line2) | 93,4% |
| OP65(Line3) | 90,4% | OP65(Line3) | 91,8% | OP65(Line3) | 89,4% |
| OP65(Line4) | 51,0% | OP65(Line4) | 53,8% | OP65(Line4) | 53,1% |
| OP73(Line1) | 78,7% | OP73(Line1) | 61,4% | OP73(Line1) | 67,1% |
| OP73(Line2) | 71,9% | OP73(Line2) | 65,2% | OP73(Line2) | 81,6% |
| OP73(Line3) | 58,0% | OP73(Line3) | 70,5% | OP73(Line3) | 64,5% |
| OP90(Line1) | 88,1% | OP90(Line1) | 86,9% | OP90(Line1) | 88,8% |
| OP90(Line2) | 56,3% | OP90(Line2) | 57,8% | OP90(Line2) | 57,4% |

The maximum number of agents waiting in the queues is summarized in Table 4.7; these values will be used as shown in Chapter 5 to compute the buffers floor area inside the plant.

TABLE 4.7: Max number of agents waiting in each buffer after model update

| Station | Agents |
|---|---|
| OP20 | 2 |
| OP30 | 6 |
| OP40 | 6 |
| OP50 | 8 |
| OP60 | 10 |
| OP70 | 6 |
| OP80 | 2 |
| OP90 | 15 |
| OP100 | 1 |

In fact, independently simulating a reduction of 1 parallel machine for each of the stations with low utilization the number of agents waiting in the queues is:

- 28 before OP30
- 65 before OP40
- 36 before OP50
- 61 before OP60
- 45 before OP70
- 83 before OP90

The number of buses waiting in the line would have been very high reducing the overall process efficiency and increasing considerably the space required for buffers inside the line. The final line structure with the new number of parallel machines is visible in Figure 4.4.

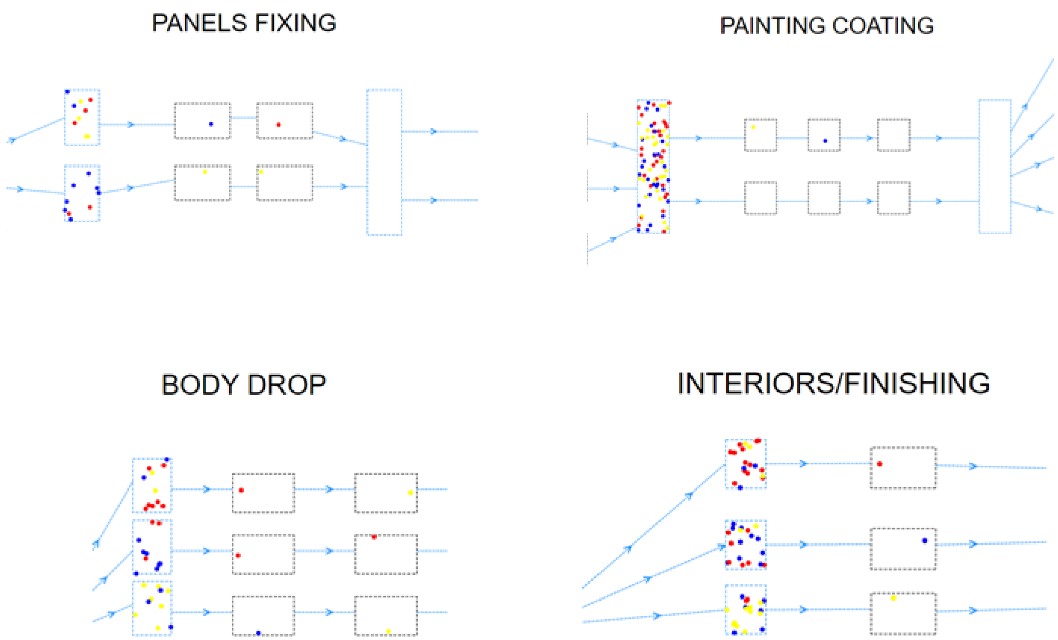



FIGURE 4.3: Examples of queues sizes with a reduction of parallel machines (OP30, OP40, OP50, OP60)

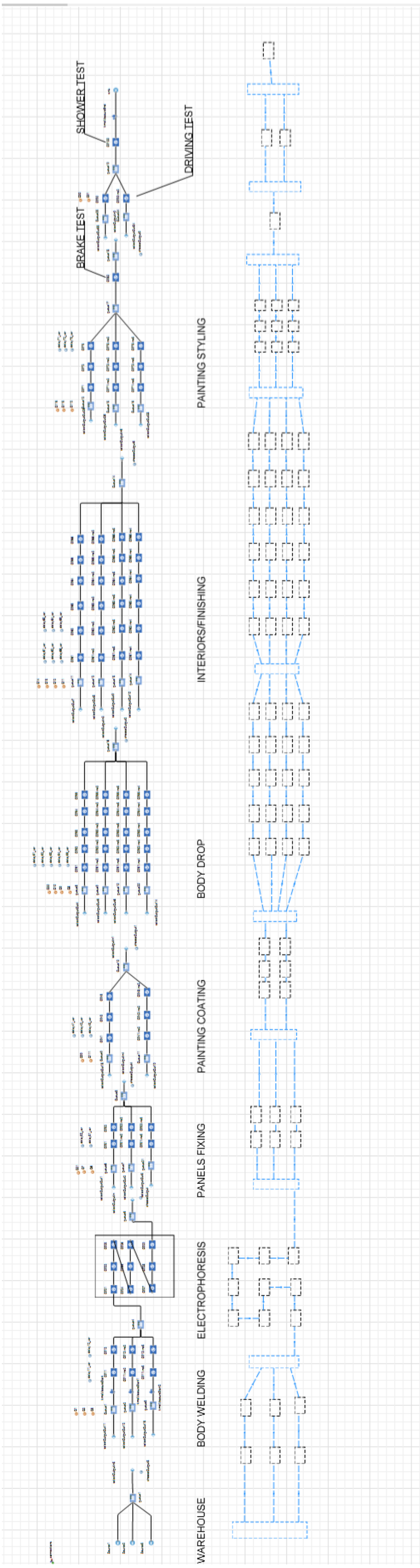



FIGURE 4.4: Final model structure

### 4.2.2 Internal benchmarking

In order to conclude the optimization process it is useful to perform the internal benchmarking activity again. As for the deterministic case, 4 conditions have been chosen to evaluate CT and TH:

- w = $W_0$
- w = $\frac{5}{4}W_0$
- w = $\frac{3}{2}W_0$
- w = $2W_0$

with the new line parameters (product mix 1) :

- $u_{MAX}$ = 0,931
- $r_b$ = 0,782 pz/h
- $T_0$ = 50,17 h
- $W_0 = r_b \cdot T_0$ = 38,72 pz

Analysing the position of the blue dot which represents the different working conditions, it is possible to say that the line has good performances regarding the CT while the TH can be further improved. However, since the reached TH is not so far from the Good area and since the final line output fulfils the yearly target, the achieved final layout is already considered as an already optimum configuration.

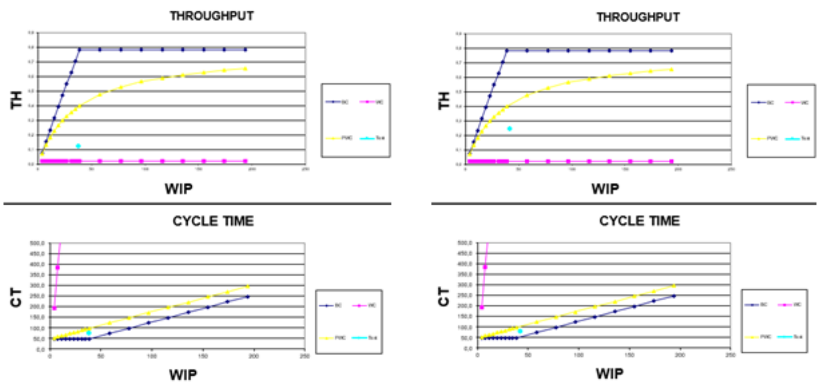



FIGURE 4.5: w = $W_0$ and w = $\frac{5}{4}W_0$

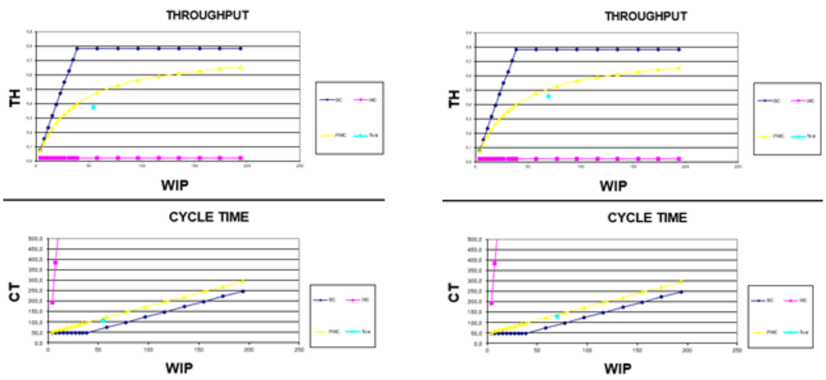



FIGURE 4.6: w = $\frac{3}{2}W_0$ and w = $2W_0$

### 4.2.3 Additional simulation: prolonged machine failures

The simulation modelling is a risk free environment that allows the possibility to compare several scenarios and systems behaviours in different working conditions: once developed the model it is easy to provide updates and changes in order to match a real case situation or problem and to predict its behaviour.
For example, the model developed so far has been analysed considering that the line is always fully working; sources of variability like failures have already been considered and they led to an increment of the effective time spent by the bus in each step of the assembly process.
However, it is interesting to consider how the line would behave in the case of prolonged failures in different workstations:

- Assembly of body structure station (OP10)
- Painting coating station (OP40)
- Painting finishing station (OP70)

The first station has been chosen since it is the bottleneck one and also the first one: an failure would have a severe impact on all the line.
The painting stations, instead, are characterized by equipment which is very reliable but an eventual failure would require higher repair resources in terms of time and money. Therefore a prolonged stop is more likely to occur in these stations rather than in other ones.

For all these stations, 1 line is blocked independently and a simulations are performed to collect the results.
The prolonged failures are implemented in AnyLogic using:

- Hold block
- Event blocks
- Variables

The Hold is placed in the line and blocks the flow of agents in a particular branch preventing their passage from the Queue to the Delay.
The modelled failure occurs after 1235 h the start of simulation and lasts 115 h, which is equal to 2 weeks working at 11,5 h/day. It is triggered by an Event block which, using a Boolean Variable, provides the information to the Hold starting the blocking activity. Other two Events are used to trigger the change temporarily the values of the queues in order to prevent the passage of agents from the SelectOutput to the Queues before the Hold.

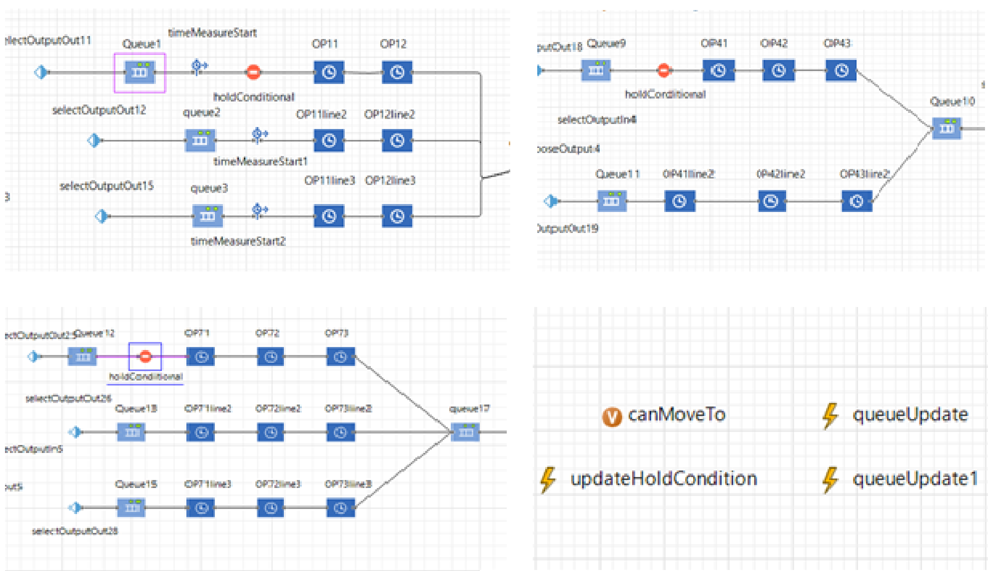



FIGURE 4.7: Failure blocks

TABLE 4.8: Failure event characteristics

| | |
|---|---|
| Failure duration [h] | 115 |
| Failure duration [days] | 15 |
| Simulation [h] | 2.470 |

Table 4.8 shows the failure event characteristics while Table 4.9 the resulting line output and the related reduction.

TABLE 4.9: Output variation due to failure

| **Station** | **Output[buses/year]** | **Reduction [%]** |
|---|---|---|
| OP10 | 782 | 14,3 |
| OP40 | 779 | 14,8 |
| OP70 | 832 | 10,9 |

# Chapter 5

# Assembly line plant

This Chapter is devoted to give an overview about important aspects of the whole production process which constitutes the working environment for the bus assembly line.
In particular will be provided:

- A description about the typical material handling equipment employed in the assembly process
- The evaluation of the workforce
- The presentation of the of the main storage systems
- The dimensioning of the auxiliary areas and employee facilities

The information provided by these analysis have been used for preliminary dimensioning of the plant occupation surface to host the bus assembly process.
The aim is to give to the designed assembly line, which is at the beginning a virtual standalone entity, the connotation of a physical process embedded in the plant production environment; this has been achieved with a first step design process degree of detail.

## 5.1 Material handling equipment

### 5.1.1 Typical MHE for bus assembly line

The described equipment has been selected according to the assembly stage of the product and the task performed in each workstation.
In particular it will be described the equipment required to:

- Move the item to the station
- Perform the tasks
- Move the item to the following station

Besides, the relevant working and geometrical parameters of the equipment are evaluated.

**OP10 - OP20**

The steel modules coming from the warehouse have to be carried to OP10 to perform the assembly of the body structure of the bus.
The modules and the relative necessary components are typically moved using:

- Forklifts
- Pallet Jacks
- Trolleys
- Overhead crane

FIGURE 5.1: Electric forklifts and pallet jack, available at [9]

The forklifts can be electric or provided with an internal combustion engine; since this equipment is intended to work primarily inside the line the first solution is more suitable and as a consequence a battery charging room has to be present inside the plant. They are provided with a mast that can swing and a carriage

along which the pair of forks are lifted.
The load capacity can vary in a wide range from 600 kg to 10 ton in the case of larger models and this parameter directly affects the minimum required aisle width.
An example of employed forklifts is the 3 wheel electric model showed in Figure 5.1 which has:

- Load capacity [t] : 3
- Minimum aisle width [m]: 3.25
- Max travel speed [km/h] : 16
- Max lift speed [m/min] : 23
- Max gradeability at full load [%]: 25

The pallet jack offers a higher manoeuvrability due to possibility of pivoting which leads to a reduced radius curvature; on the other hand its use is limited to applications where the operator does not have to cover long distances and whenever the requested load capacity is lower than 5 t.
To conclude, it is possible to say that both the configurations are suitable to transport the modules (properly placed in support and carrying items as pallets) from the warehouse to OP10, while the forklifts have a wider range of applications inside the line. A solution for smaller pieces and sub-modules is represented by the trolleys.
They are usually made of aluminium or steel platforms and can be provided for specific tasks with a handlebar.
They usually have 4 casters: 2 swivels and 2 rigid offering high manoeuvrability.
Typical trolleys features values are:

- Load capacity [kg] : 300 - 1300
- Platform size [mm]: 600 - 900 x 900 - 1800
- Platform height[mm]: 230 - 300
- Handle height (mm): 910 - 980

The bigger parts of the modules (or even whole modules) are moved using an overhead hanger moved by a crane. They are placed on specific body assembly equipment that supports the body modules (floor, sides, front and rear) helping the operators in the positioning and the welding activities from an elevated position.

FIGURE 5.2: Body assembly equipment, available at [10]

The hanger is composed of a frame, a set of 2 hooks, adjusting fixtures, pneumatic control and it is used to lift the assembled body structure.
Typically, the employed cranes have:

- Lifting capacity [t]: 1 - 10
- Span [m]: 7.5 – 22.5
- Maximum speed [m/min]: 20

The hook can be driven either by the plant energy source or by the built-in air source.
At the end of OP10, the whole structure is positioned on platform trolleys or on an electric rail cart.
The electric rail carts are battery powered and can be operated using buttons or in a remote way. The rails, even if their presence reduces the usage flexibility, offer the possibility to increase the stability and therefore giving the possibility to have a high load capacity and table sizes (whose dimensions are customizable) are useful for bulky items. Typical values are:

- Load capacity [t] : 2 - 150

- Wheel base[mm]: 1200 - 8000
- Running speed [m/min]: 0 - 30

FIGURE 5.3: Overhead hanger and crane , available at [11]

FIGURE 5.4: Trolley with handlebar and electric rail, available at [12]

The electric cart appears to be a more efficient (and expensive) solution with respect the trolleys but the choice between them is strictly dependent on geometrical constraints of the line and the possibility of rails installation.
The structure is moved to OP20 where undergoes several chemical treatment in the electrophoresis department. It is lifted using a rail conveyor system which allows to have a precise control on the vertical and horizontal movements of the item in the manoeuvres among the different tanks.


FIGURE 5.5: Electrophoresis equipment , available at [13]

**OP30 – OP40**

In order to help the operator in the assembly operations of the panels all around the bus it is lifted using special devices called mobile columns.
They are battery powered and wireless connected one to each other to make them work individually, in pairs or all at one.
Their features are:

- Fork length [mm]: 350
- Load capacity [t]: 7.7 - 11

Using trolleys the bus is then moved to OP40 for the coating painting. The bus, whose weight is now considerably increased, are moved using tractors. These devices are battery powered, which provide for more than 15,000 of operative hours and a carrying capacity up to 25 ton. Inside the painting station the bus is moved using floor conveyors moved by belts or chains as visible in Figure 5.8.

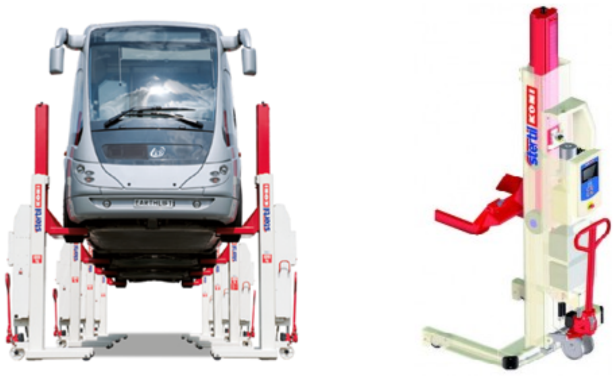


FIGURE 5.6: Mobile column lift , available at [14]

FIGURE 5.7: Electric tractor, available at [15]

FIGURE 5.8: Floor conveyor, available at [10]

**OP50 - OP60**

The bus coming outside the coating painting station has to be lifted again to allow the fixing the underbody to the body structure in OP50.
To move the bus from one substation to another it is lifted and placed on wheeled platforms which can be fixed to floor with rails to have a better handling during the movements.
These platforms allow to have the bus constantly lifted to perform tasks all around it. At the end of the body drop station the bus can be even started and moved inside the line on its own wheels since the basics mechanical components and the propulsion system have been mounted.
Sometimes this possibility is prevented whenever a proper air circulation cannot be guaranteed inside the line due to the combustion engine pollutant emissions.

FIGURE 5.9: Lifting platform, available at [10]

In OP50 and OP60 most of the activities are performed manually. Anyway, the heavy weight of engine and of mechanical components require the use of forklifts or picking trucks; with a very similar design to a traditional forklifts the picking truck allows the operator to be lifted on a platform.
For the windows positioning a glass plate vacuum lifting is employed instead. This device exploits a wall mounted crane and a pivoting system and provide a

maximum carrying capacity of 80 kg.

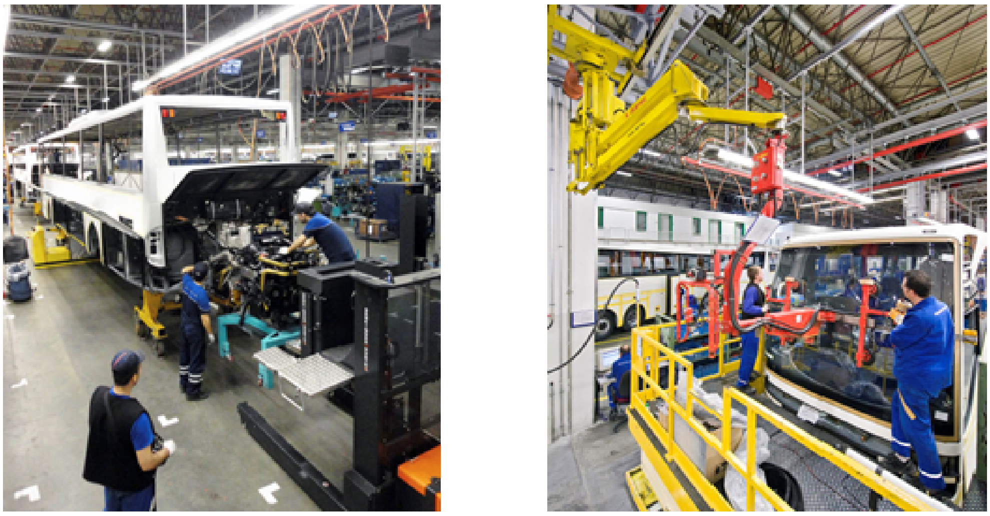


FIGURE 5.10: Picking truck and glass vacuum lift, available at [10]

### 5.1.2 AnyLogic Conveyor block

In order to evaluate how the presence of the described material handling equipment can affect the line performance the Conveyor block is employed. This element moves the agent at a defined speed and along a path of defined length; by default the agents speed is defined univocally for all the simulation areas but thanks to this block it is possible to locally modify this value.
Therefore, in order to the refine the simulation and verify that the MHE presence does not prevent the line from reaching its production target, the overhead conveyors present in OP10 and OP20 are modelled using the Conveyor block.
In particular the Conveyor block has been employed to simulate the motion of the body structure:

- From the first substation to the inspection location
- From the inspection to the electrophoresis station
- Among the substations of the electrophoresis station

The choice of modelling the overhead conveyor is due to the fact that its average travelling speed has been computed as 0.5 km/h, while the default agents speed

has been set at 4 km/h for the whole simulation.
This value takes into account the reduction of speed of the overhead conveyor with respect the maximum value (1/1.5 km/h) due to loading and unloading manoeuvres of a such a bulky item as a bus and represents the slowest type of MHE inside the line.
Anyway, in order to evaluate properly the MHE performances a devoted detailed simulation would be required and it is beyond the aim of this thesis work.
The 4 km/h agent speed has been set considering that for several workstations the bus is manually moved by operators using trolleys and wheeled lifting platforms and most of the assembly operations are done inside the plant building where it is more difficult to turn on the bus engine due to pollutant emissions.

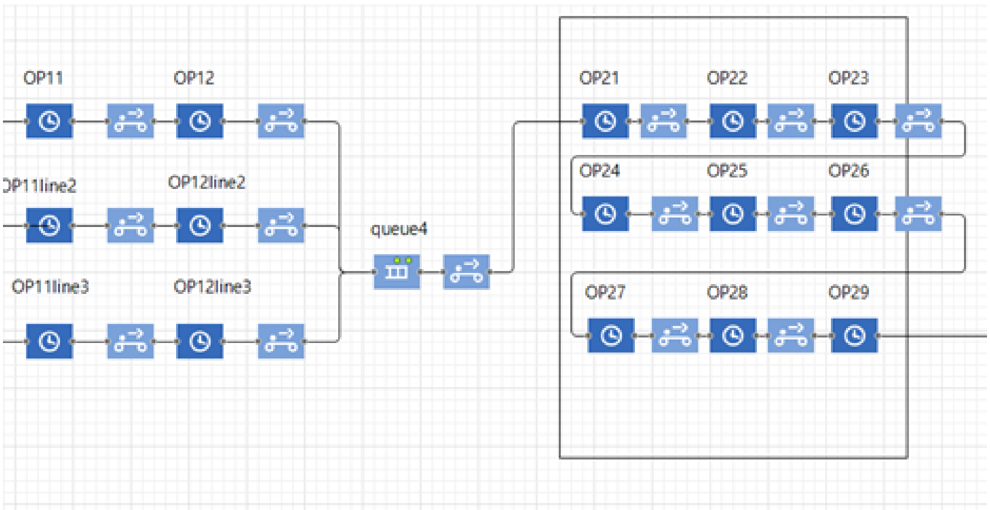



FIGURE 5.11: AnyLogic Conveyor block

As it was predictable, after this model update the line performances results not to be significantly affected by the overhead conveyors speed reduction.
This is because the variation of time introduced by this MHE is much lower with respect the duration of the single workstations and the overall duration of the simulation.

## 5.2 Plant layout

### 5.2.1 Workforce computation

The evaluation of the necessary workforce requires the analysis of the tasks performed in each station.
In OP10 the 6 modules of the top body structure have to be positioned on the assembly racks using an overhead crane and then they have to be welded together; 1 worker has to control the crane and the other 3 have to position the modules on the rack. During the welding activity all 4 workers participate to the process. A fifth operator performs inspection of the obtained body structure.
The electrophoresis treatment carried in OP20 is a highly automated process thus only 3 workers are required: 1 to perform the preparation activity as the preliminary polishing , 1 to deal with the control of chemical process parameters and a third for the final inspection.
In OP30 the external panels are fixed: 4 workers are needed to install the panels using gluing process, 2 for each side of the bus; a fifth operator performs the inspection.
In OP40 the first painting process is performed, 2 operators are required to clean, dry sand the vehicle and 2 to apply the coat painting. The bus is then moved to the drying and curing process zone where a visual inspection is performed by a fifth operator in the end.
Before the body drop activities, which takes place in OP50, some wires and pipes are positioned in the bus: 2 operators are required.
Through welding process, the body structure is assembled on the chassis: 4 workers are required for this activity, 1 to command the overhead crane and 3 to position the structure and align it on the chassis. Once the top structure is aligned on the chassis the 4 workers weld together. During this activity, in the following substations, three more operators are present: 2 for the engine assembly operations and 1 for the inspection process.
In OP60 the assembly of electrical wires, interior panelling, seats, HVAC system and windows takes place in 6 different substations: 2 operators are on average required for each substation.
In OP70 the second painting process takes place with activities similar to the ones performed in OP40 with 5 total workers involved.
The last three stations OP80, OP90, OP100 require 2 operators for each parallel

machine: 1 operator physically driving the bus to assess performances for the brake, driving and shower test and another one involved in the inspection activities and data collection.
Once having defined the number of workers for each line, the total number of workers required for the whole assembly process has been calculated considering the total number of lines present in each station.
Therefore the total number of operators involved directly in the assembly operations is 150. The results are presented in Table 5.1

TABLE 5.1: Assembly workforce

| Station | Workers/Machine | Machine/Station | Workers |
|---|---|---|---|
| OP10 | 5 | 3 | 15 |
| OP20 | 3 | 1 | 3 |
| OP30 | 5 | 3 | 15 |
| OP40 | 5 | 2 | 10 |
| OP50 | 9 | 4 | 36 |
| OP60 | 12 | 4 | 48 |
| OP70 | 5 | 3 | 15 |
| OP80 | 2 | 1 | 2 |
| OP90 | 2 | 2 | 4 |
| OP100 | 2 | 1 | 2 |
| | | | TOT = 150 |

The previous computation involved the total number blue collar workers.
In order to properly manage the and supervise the operations a total of 13 white collars is required: 1 for each workstation, 1 for the storing areas , 1 for the finished buses and 1 for the management of the staff.
The sum of the blue and white collars is called direct workforce.
The indirect workforce is instead the sum of the staff and of the operators not directly involved in the assembly operations; the number of these operators has been computed as 20% of direct workforce and also accounts for the operators involved in warehouse, shipping and receiving areas.

The total workforce present in the plant is the sum of the direct and indirect workforce and the results is visible in Table 5.2.

TABLE 5.2: Total plant workforce

| | |
|---|---|
| Assembly workforce | 150 |
| Supervisors | 13 |
| Direct workforce | 5 |
| Indirect workforce | 5 |
| TOT | 196 |

### 5.2.2 Storage systems

The main storage areas present in a bus manufacturing plant are:

- The chassis parking
- The warehouse

The chassis parking is an area devoted to host the chassis frame waiting to be processed and properly adjusted in length to match the size of the bus body structure; the fixing and assembly procedure in typically called "marriage" and takes place in OP50.
This area is always placed outside the plant building, it must be easily accessible for the car transporters and it is not provided with a roof covering.
The warehouse is instead usually placed close to the first assembly station since the modules that compose the body structure are quite bulky to transport.
The bus is a quite complex item to manufacture with a multitude of components as a passenger car but differently from it, their dimension and weight is considerably higher.
Therefore, in a bus manufacturing company warehouse person to item systems are more common than item to person ones.
Item to persons systems (as for example AS/RS) a far more complex and expensive solutions and they are usually not employed by a medium size bodybuilding company like the target one.
In the person to item storing systems the items operator moves to the item and places it inside/to the devoted storage location.

The storage system of this category usually employed in a bus assembly warehouse are:

- Stack systems
- Traditional racks
- Pushed back racks

The stack system is suitable for light weight components that can stacked one on the other using stackable pallets.
The common pallet typology is the double face Euro-pallet 1200 x 800 [mm]made in wood; for heavy weight components also metal stackable systems are employed with corner supports and they are used not only in the storing operation but also in the transportation activities.
The stack system is a simple and re-configurable system and allows high utilization of the storage space with low investment cost but with the main disadvantage of a selectivity $\leq 1$.
This relevant index is the ratio between the number of directly accessible types of products over the total number of types in a storing system; this index changes with the chosen storing system and has to be always considered in the warehouse design.In the case of a stack it means that clearly not all the items stacked are accessible without moving other ones, unless they are all of the same type.
Usually lightweight components are stored using this system as external panels, interior components, light mechanical components, dashboards elements etc.
Due to reduced number of levels, a traditional counterbalanced forklift can be used by the operator to pick or place the pallet with box as the one employed in OP10.
The traditional rack storage allows with a simple equipment to store heavier components, placed in boxes on top of pallets, having a selectivity = 1. This means that different components can be placed close without the disadvantage of removing a pallet to reach another one.
This system can be designed to efficiently exploit the warehouse space due to its regular and modular shape This structure can be customized in dimension but typical choices are to allow the storing of one or maximum 2 pallets next to each other on the same level.
Due to the sustain offered by the rack structure, heavier components can be stored

as mechanical parts, doors and seats elements etc.
During the design of a rack system the number of levels are define considering:

- Floor carrying capacity
- Available height below truss

The chosen number of levels affects the MHE decision.
Due to the possibility to reach a higher number of levels compared to the stack system, a side loaders or a turret picking truck can be employed rather than a forklift.
Side loaders are equipped with forks which are side shifted and are designed to work in narrow aisle. They have lifting height up to 13-14 m and thus are equipped with rails (mechanical or magnetic) that prevent the side loader to capsize.
Turret picking instead are provided with a cabin that allows the operator to be lifted and manually picking items or better perform the lifting operations. As the side loaders they are provided with floor rails or cables for stability and their reachable height is usually up to 8-10 m.

FIGURE 5.12: Side loaders and turret picking, available at [9]

A similar configuration is offered by the cantilever racks which allow the storing of items of higher length compared to the traditional rack systems.
Each shelf level is composed of 2 horizontal arms connected to vertical columns;

to give more strength to the whole structure bracing are placed between the columns.
They are employed for long structural elements, floor panelling, ramps components, wirings and with suitable design for glasses plats etc.
The push back systems are equipped with carts which allow the unit load to move. They can exploit an automatic system or the gravity; this second method is simpler and less expensive and it works exploiting the rack slope (about 3 °) and the items weight to move them. The pallets are placed on the carrying cart and pushed into the rack in turn. The forklift does not need to enter the rack and the operation method is similar as the one of traditional racks.
The overall selectivity index is <1 but since multiple pallet positions can be designed in the rack depth direction it allows to differently exploit the warehouse available space complying with shape constraints.

FIGURE 5.13: Cantilever racks and pushed back rack, available at [11]

In the end in automotive warehouse special storing systems are employed for engines, differential and other heavy weight mechanical components.
In the case of a second phase manufacturer these elements are purchased from outside companies as the frame chassis and are stored mainly in devoted storing areas close to the marriage station and the chassis parking.
A devoted numerical analysis of the required space to store all the components of an urban bus and an inner detailed design is beyond the aim of this project work.

### 5.2.3 Employees facilities and auxiliary areas

Once defined the workforce it is possible to dimension the main plant employees facilities.
In particular for employee facility, the reference has been Chapter 9 of [5].
In particular the following choices have been made:

- Lockers: 1 for each blue collar worker, 2 $m^2$ for each locker
- Restroom: 1 toilet every 10 employees, 2 $m^2$ for each toilet
- Lunchroom: 1,5 $m^2$ per employee including eating area, serving line and food preparation area + 200 $m^2$ for auxiliary operations
- Medical facility: medical room space 50 $m^2$ equipped with safety and health measures control function and a first-aid intervention kit
- Offices: 15 $m^2$ for supervisor
- Staff offices: 15 $m^2$ for staff employee
- Parking lots: number of spaces equal to 50% of total employees
- Break areas: 20 $m^2$ each

For people with disabilities it is necessary to add 1 toilet for each group of toilets with a minimum floor area equal to 3,24 $m^2$.
The auxiliary areas have been chosen as:

- Main driveways: width 5 m, compatible with the forklift width
- Walkways: 1 person 0,6 m width, 2 persons 1,2 m width
- Emergency door: 1,2 m width
- Entrance door: 2,4 m width

Besides it is necessary also to devote space for:

- Battery charging room, where the removable batteries of tractors and forklift can be replaced and charged
- Tool and maintenance room

- Training room, useful for workers training or meetings

The warehouse floor occupation required a devoted detailed analysis beyond the aim of this project work.
Anyway exploiting available data present at INSIA about other Spanish bus companies which adopts a similar assembly process, the warehouse space occupation has been set as 7000 $m^2$ ; this has given the possibility to perform a preliminary evaluation of the whole plant floor occupation.
The results of the computation of the employees facilities and auxiliary areas in terms of floor space occupation are summarized in Table 5.3.

TABLE 5.3: Employees and auxiliary areas floor occupation

| **Area** | **[$m^2$]** |
|---|---|
| Lockers | 300 |
| Restrooms | 40 |
| Lunchroom | 425 |
| Medical facility | 50 |
| Supervisors offices | 195 |
| Staff office | 75 |
| Training room | 100 |
| Tool and maintenance room | 300 |
| Break areas (2) | 40 |
| Battery charging room | 50 |
| TOT | 1.475 |

### 5.2.4 Final layout

In order to give a physical connotation to the line layout simulated using AnyLogic, the floor surface required for each workstation has been computed.
The starting point is the definition of the minimum bus floor area.
According to the sizes of the assembled buses, the different bus floor areas are:

- 10,000 x 2,550 [mm]
- 12,000 x 2,550 [mm]

- 15,000 x 2,550 [mm]

The 15 m bus area has been used as the reference value.
A working area of 20,000 x 7,650 [mm] has been chosen as the reference surface to account for the space required for the assembly activities performed by the operators in each workstation around the buses; this area is visible in Figure 5.1
In the following images their colour is different for each OP.
Besides, buffers are positioned between each workstation.
Their size has been chosen to host the maximum number of buses simultaneously waiting to enter in the following station; buffers are represented in blue while the waiting buses in red as visible in Figure 5.2
These values (as well as the number m of parallel machines in each workstation) have been already described in Chapter 4.

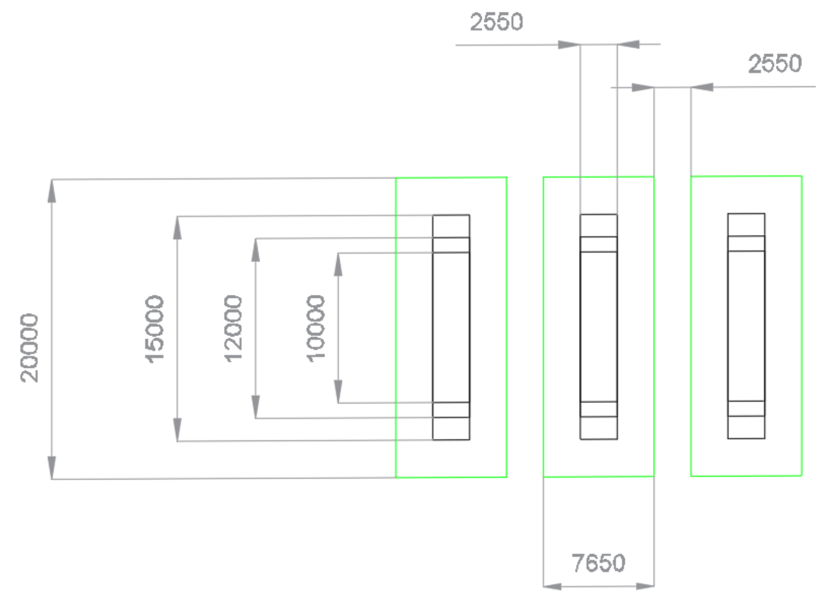



FIGURE 5.14: Bus unit floor and working area

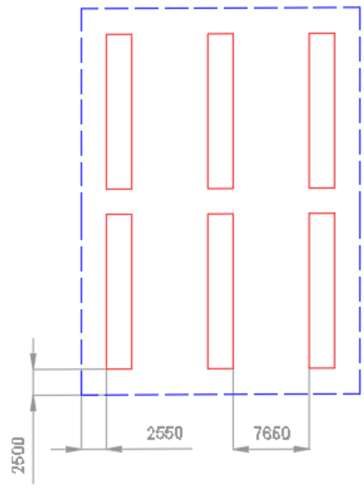



FIGURE 5.15: Example of queue floor area and waiting buses

In computing the electrophoresis floor occupation, 15 m of horizontal distance has been taken into account to allow the bus manoeuvres to enter and exit in the queue.
The dimensions of the outside area useful to perform the drive test on the bus has, instead, has dimensions 200 x 50 [m].
Therefore, it has been possible to draw a preliminary 2D model of the line structure using AutoCAD.

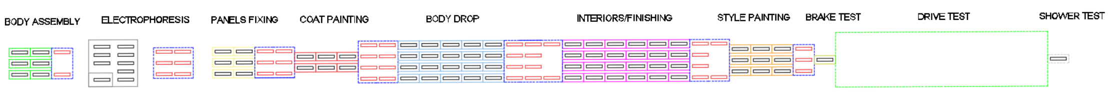



FIGURE 5.16: Preliminary line layout

Actually, this linear configuration is not feasible and efficient inside a plant and thus U shaped layout has been defined accomplishing a more regular design.
This layout has been imported in AnyLogic and the space mark-ups of delays and queues blocks have been superimposed on the CAD drawing.
The final layout obtained in AnyLogic is a simulation environment where the agents motion and location match a real physical space that takes into account the bus size and providing the minimum space for the assembly operations.
In the following image is possible to see the coloured dots representing the agents flowing in the stations and coming out as 2D representations of finished buses.

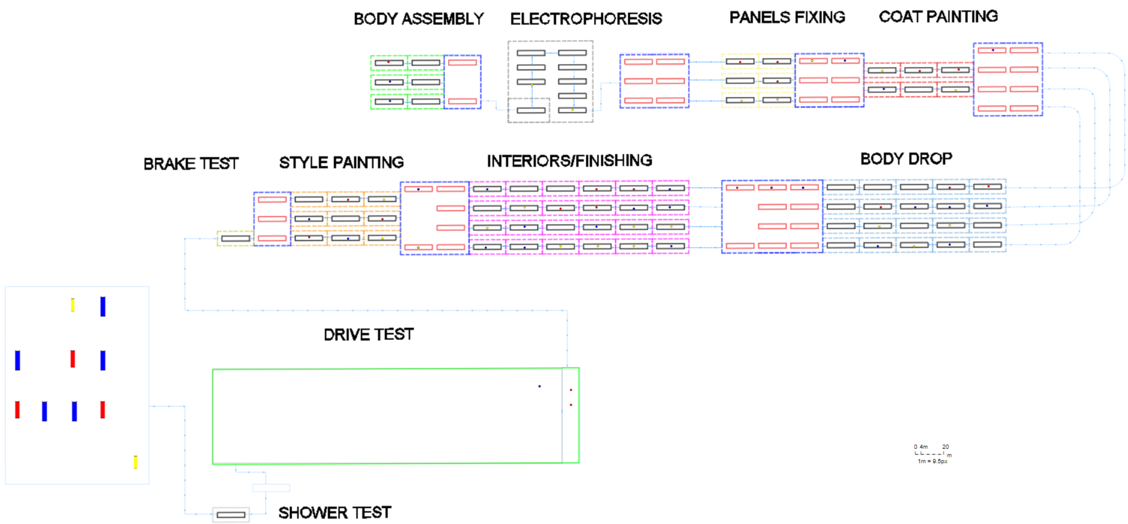



FIGURE 5.17: AnyLogic space mark ups update

In order to complete the CAD representation, the auxiliary areas and employees facilities have been added.
Therefore, it has been possible to integrate the assembly line inside the plant building.

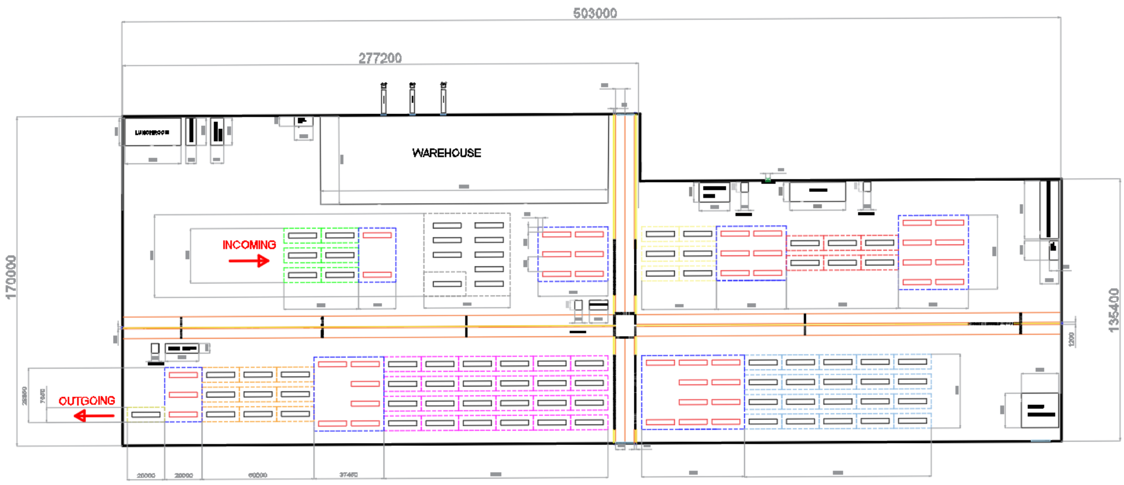



FIGURE 5.18: Plant Layout

The red arrows define the direction of the assembly line motion inside the plant defining the entering of incoming body structure modules inside OP10 and the exit of finished bus from OP80.
The plant is characterized by:

- 2 main aisles: in the central one the pedestrian aisles are placed on the sides and the driveways in the middle while in the horizontal aisles the pedestrian walkways are in the middle; in this case the walkways are protected by metal bars parallel to the floor.
  In both the main aisles two lanes for each motion directions are present; zebra crossings are placed to allow the passage of pedestrians at the intersections.

- Emergency doors are located at the end of each walkways and industrial doors at the end of driveways; they are also present close to OP50 to allow the passage of the chassis and in the warehouse.

The main choices related to the location of the employee facilities and auxiliary areas have been:

- Supervisors office, lockers close to the main entrance

- Medical facility at the intersection of main aisles

- Battery charging room easily accessible from driveways
- Staff office close to brake test and away from central production areas

The external main building dimensions are 503 x 170 [m]. In the end, in the Master Plan is possible to see:

- OP90 and OP100 located outside the building
- The chassis parking close to OP50
- The finished bus parking
- The employee parking spaces close to the main entrance

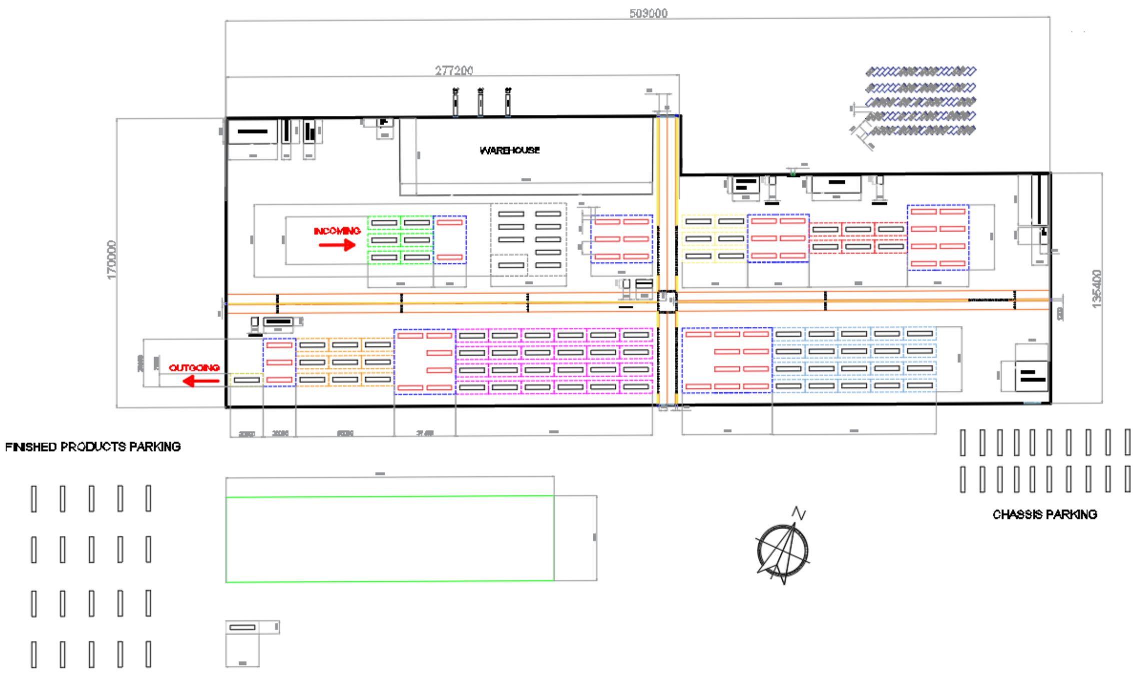



FIGURE 5.19: Master Plan

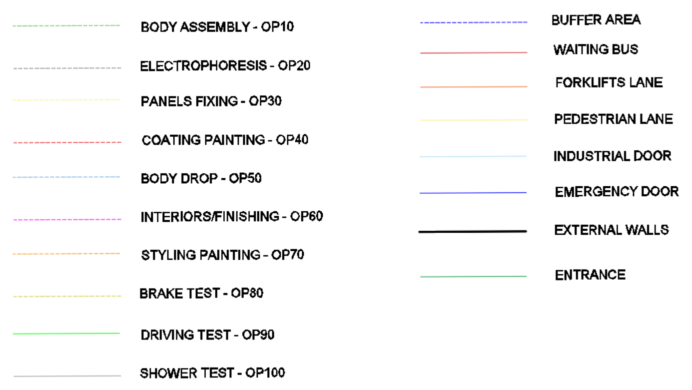



FIGURE 5.20: Legend

# Chapter 6

# Conclusions

## 6.1 Results

In this thesis work it has been possible to perform the design and the optimization of an urban bus assembly line.
First, the steps necessary for the bus manufacturing process have been defined exploiting INSIA experience and they have been validated by a Spanish bus body building company.
With the use of AnyLogic a suitable model has been implemented and several simulations have been performed in order to verify the compliance with production line targets.
In a cyclic optimization process it has been possible to obtain:

- The workload balancing among the parallel machines that compose each workstation
- The definition of line bottlenecks
- A dimensioning of necessary buffers between the workstations

In order to assess the line performances in different working conditions, several scenarios are simulated in particular product mixes and production shifts are changed and the response of the model to these input variations have been analysed. In addition the events of prolonged machine failures have been modelled to evaluate their effects on the line performances.
Besides, probability distributions have been employed in order to bring the obtained model closer to a real case system taking into account failures, setups and reworking activities.

In the end, for the sake of a more complete comprehension of the industrial environment in which the line works:

- The typical material handling equipment and storing systems have been presented
- The required workforce has been computed
- The floor areas required for the assembly operations, employee facilities and auxiliary services have been calculated

Therefore, it has been possible to preliminary dimension and define the layout of the whole industrial plant using AutoCAD.
It represents a preliminary step in the design process of the whole production facility.

## 6.2 Future improvements

The abstraction level employed with the discrete event simulations has been set to allow to have a complete overview of a year of production to validate the general structure of the line.
Anyway, the definition of the line structure achieved with this work offers a starting point for a future refinement analysis.
In particular it is possible (with a DES or a multi-method simulation modelling) to compute in detail the necessary resources (MHE and workforce) for one or more workstations of the assembly process. This is possible switching to a lower abstraction level which leads to a higher level of details as the knowledge of the inner design of each workstations and machines.
Furthermore, with this higher level of detail, it is also possible to design the warehouse and to define the shipping and receiving areas refining the dimensioning of the whole plant facility.
To conclude, it is worth to underline that this work lends itself to be employed in a wider range of scenarios other than the urban bus manufacturing industry, due to the efficiency increase that a simulation software like AnyLogic offers in many other applications.

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