POLITECNICO DI TORINO

Master's Degree in Automotive Engineering

Formula student cars assembly plant design and material handling optimization

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1. Introduction

1.1 The objective

The thesis deals with the plant working areas dimensioning and material handling processes optimization for the assembly operations of a Formula Student Racing car assembly line, which main characteristics and parameters will be defined in the following.

This project is aimed at helping the 'Instituto Universitario de Investigacion del Automovil Francisco Aparicio' (here after simply 'INSIA') of the Universidad Politecnica de Madrid (in the following 'UPM') in a business case related to a hypothetical growth of the production of the formula student racing car.

The business case, as it is made explicit by the official document "Formula Student Rules 2020" is truly part of the real competition students have to undertake. Under this point of view, it has been required to me to help the team to understand how the production of their car could be standardized thus providing results in the industrial plant field of study. Gained these, their ability to compete in the business case would be enhanced, considering aspects that would be not exploited otherwise.

These being the requirements of the official Formula Student Rules 2020 competition catalogue, under the section S1 called "Business Plan Presentation Event (BPP)":

"The objective of the BPP is to evaluate the team's ability to develop a comprehensive business model which demonstrates their product – a prototype race car – could become a rewarding business opportunity that creates a monetary profit".

This project was needed in order to provide a solid basis to the team to perform the economical evaluation since the technical aspects laying underneath the industrialization of the vehicle have not been deeply analyzed previously.

This project has been developed in the environment of an international experience funded by the Erasmus+ Programme Country 'mobility for final project development' program.

Figure 1 Insia FSAE car 2019

1.2 The method

This project is mainly divided into two sections and their results.

The first is aimed at the definition of the main parameters of assembly and the dimensioning of the plant. For this reason, a complete analysis of the assembly consisting in the choice of the assembly plant, assembly layout, workforce and material handling equipment is done as first step. In fact, this is necessary to have a complete view for the optimization of the assembly plant and the analysis of possible growth of the annual assembly rate.

In this first section, many assumptions will be done. This is given by the fact that for the first time a radical change in the production and assembly of this kind of car is assumed, passing from a complete hand-assembled car to an implementation with more developed material handling equipment tools, typical of way more technological assembly line such as the one of mass production. Material handling equipment analysis will be performed to optimize the ergonomics and the workforce utilization.

In the second section the implementation of the same assembly plant is developed using the software Anylogic. Characteristic of the software will be explained in due course. Anyhow, this part of the work will be very important to analyze in a probabilistic manner the assembly rate increase, that at a first attempt, will be dimensioned based on the initial required production of 1000 units. Hereafter, line validation and balancing will be performed by means of the software such as 2D material handling simulations.

Eventually, the project will display an assembly plant layout able to sustain both the minimum deterministic required production such as to undergo a certain amount of process variability. All this, with the optimization of material handling equipment tools.

1.3 The tools

For the first part of the work, whose main aim is the definition of the assembly plant layout and first material handling equipment tools, spreadsheets for the analysis and evaluation of assembly rates, working hours and so on are used. The software used for this **analytical model** evaluation is Microsoft Excel. Towards the end of this section, Autodesk AUTOCAD software will be used for the graphical implementation of the plant.

Drawings from the INSIA car development team are provided, mainly for the material handling decisions. These specifications cannot be displayed and will be kept secreted for the whole project.

On the other hand, lines and processes validations will be performed with Anylogic. With this, an **Agent based** simulation model is created and results are later on analyzed. Here on, the material handling can be analyzed too thanks to the particular libraries that are present in the software. All the used ones will be explained after.

2. The base annual production: plant layout and dimensioning

This first big part of the project is aimed at evaluating all what concerns the required base production. The business plan that has to be developed requires an annual assembly volume of 1000 units.

This part concerns with the **plant design**, defined as the process planning the right equipment, coupled with right place, to permit the processing of a product unit in the most effective manner, through the shortest possible distance and in the shortest possible time. [1]

2.1 A completely new challenge

In this section the main guidelines and constraints related to the project will be analyzed. The first fundamental thing to be taken into consideration is the change in the kind of production. This means that **for the first time** it is supposed to model an assembly line for a product, the formula student racing car, which usually is assembled by operators, and produced in one, maximum two units per year for each championship. Thus, this project does not require a change in the assembly technologies only, but also a change in the mentality that could make converge all these analyses to a coherent result. This represent a new challenge.

The starting point to model a problem like this one is to know the number of units that are required for year. In this case, the number is 1000. Starting from the analysis of the production number it is easy to note that it represents a kind of trade-off between the very low handicraft production that is currently performed and the much higher numbers we could deal with when talking of the so-called ‘mass production’.

In the latest case, the production or assembly volumes are way higher than the required one, reaching hundreds of thousands of units per year. Thus, it is worth to note that this production will require neither a pure handicraft production nor a completely automated one like it happens for mass volumes.

2.2 The level of aggregation

Another correct concern for the project is to have clear the level of aggregation brought on inside this work. As it is easy to note, a whatever car or similar product is made of a high number of single components, each one assembled in many different ways to create the final assembled car. Of course, it is impossible to go into such a detailed level for this project, and this is the reason why it has been decided to consider a number of modules in between 10 and 15 for the assembly project. Thus, it deals with a **first level of aggregation**.

A '**module**' represents a set of single elements that can be thought as a black box which arrives to the assembly plant closed and that only requires to be attached to the main structure of the racing car by means of different technologies.

Note the operator is not allowed to open the casing structure to look inside. This is fundamental to maintain the know-how that is involved in the creation of the different single modules, which is intellectual property of the producer. This being either be the racing car team or an external supplier. In both cases the module arrives the plant closed and has to be jointed only. On the other hand, enclosed components of the module could be divided for line balancing reasons explained in next chapters; Of course, it would happen without affecting the above-mentioned criteria.

Examples of modules can be: electrical wiring, battery pack, wheels and tires, cooling system, etc. The modules chosen and their related subcomponents are listed in the following:

1) Monocoque, divided into:
   - main hoop
   - nose
2) Front suspension, whose subgroups are:
   - Upright
   - Planetary gear
   - Electric motor
   - Brake disk and caliper
   - Up and down A-arms

- Shock absorber
- Rocket and bars

3) Steering system
4) Rear suspension, again including:
   - Upright
   - Planetary gear
   - Electric motor
   - Brake disk and caliper
   - Up and down A-arms
   - Shock absorber
   - Rocket and bars
5) Electric wiring and brake lines, divided into:
   - High voltage wirings
   - Low voltage wirings
   - Brake lines
6) Cooling system
7) Tractive system or simply “traction” whose elements are:
   - Battery
   - Inverters
   - Electronics
8) Interior elements, thus:
   - Pedal box
   - Seat
   - Safety harness
9) Aerodynamic devices, joining:
   - Front wing
   - Lateral wings and side pods
   - Rear wing
   - Diffusor
10) Wheels

2.3 Plant type and location

The choice of the module is in line with further more questions that arises during the development of the project. As already stated, the production number is not able to justify by itself the choice of the assembly layout. In fact, this number seems to be quite low.

Given that the car is being assembled in a student team context, the assembly process is neither precise nor standardized. Therefore, the standard times for the single modules cannot be obtain with a level of accuracy high enough to allow a direct shift to an industrial production. For the same reason, said standard times are not directly obtained from measurements but from an approximation that proved to be comparable to the actual assembly process.

MAIN MODULE	SUBMODULES	STANDARD TIME [min]	
		from	to
Monocoque	Main hoop	5	7
	Nose	2	3
Front suspension (x2)	Upright	30	45
	Planetary gear		
	Electric motor		
	Brake disk and caliper		
	Up and down A-arms		
	Shock absorber		
	Rocket and bars		
Steering system		15	20
Rear suspension (x2)	Upright	30	45
	Planetary gear		
	Electric motor		
	Brake disk and caliper		
	Up and down A-arms		
	Shock absorber		
	Rocket and bars		
Electric wiring and brake line	High voltage wirings (x4)	15	
	Low voltage wirings	10	15
	Brake line	20	30
Cooling system		40	
Tractive system	Battery	20	35
	Inverters	10	
	Electronics	10	20
Interior elements	Pedal box	15	25
	Seat	2	3
	Safety harness	15	25
Aerodynamic devices	Front wing	3	5
	Rear wing	3	5
	Diffusor	3	5
	Later wings and side pods	2	3
Wheels (x4)		2	

A first very rough evaluation of the time required to produce a complete car, from which the takt time can be extrapolated too, results in an average of more than 6 hours needed to completely assemble one. The following evaluation is obtained from the sum of the times as they have been given for the business case.

Please note it has been supposed to have one employee working at each station, even when multitasks operations have to be performed. That is the reason why the grey lines are not considered in the time sum.

	TIME [min]		
Name of the module	MIN	MAX	AVG
Main hoop and nose	7	10	8,5
Electric wiring with 1 person	60	75	67,5
Electric wiring with 2 people	45	60	52,5
Traction and transmission	40	65	52,5
Cooling system	40		
Pedal box , steering, seat, safety harness	47	73	60
Front suspension with 1 person	60	90	75
Front suspension with 2 people	30	45	37,5
Rear suspension with 1 person	60	90	75
Rear suspension with 2 people	30	45	37,5
Front wing and diffusor	6	10	8
Wheels in 1 person	8		
Wheels in 2 people	4		
Rear and side wings	5	8	6,5

Resulting in a total time of:

TIME [hours]		
MIN	MAX	AVG
5,48	7,77	**6,63**

The purpose of this evaluation is to understand if it makes sense to use a dedicated plant for the assembly of this racing car **or if makes sense to delegate and allocate the**

production to a different company with similar production types, like quads one for example.

Supposing to have the assembly stations working **260 days/year, 2 shifts/day** and taking into account that we need an average of one shift to assemble a car, **the first result is that a dedicated plant is required**. For this evaluation, consider a shift to be oh 7.5 working hours.

Of course, the plant can be either built brand new or converted from an already existing one.

The first solution is known as "Greenfield solution" and it should be chosen for the very high flexibility in the construction of the plant. In fact, in this case the project starts from scratch and the only structural limits present are the ones for the location of the main pillars, which could affect the assembly area layout.

The second solution, known as "Brownfield solution", exploits and already existing industrial building and convert it to the production or assembly that is needed. Of course, the limits are consistent. Hereafter, walls represent a project constraint at the same level of pillars, already located in the floor area. The positive aspect of this solution is the cost, of course. It is lower than the unit cost per meter square required in the greenfield solution.

Anyhow, given the flexibility of the project, it is preferable **to opt for the greenfield one**.

The next problem to face is related to the **geographical location** of the plant. In fact, it is required to have a plant that could be comfortable for logistics operations. It should be close to the highest number of intermodal transport points, meaning railways, harbors, and present a coherent number of docks both for receiving and shipment. Of course, the docks design will be faced during the project development. Furthermore, the plant has to be located in Spain.

For the above-mentioned reasons, one of the possible locations could be the following one, in the **industrial area of the municipality of Valencia**:

Figure 2 Satellite view of Valencian industrial area

Zooming more:

Figure 3 Zoomed satellite view of Valencian industrial area

Here, in the hearth of the Valencian industrial area, a field prone to industrial building construction has been found. Of course, this only represent an example of location. The exact geographical location is given in coordinates as follows:

Municipality of Riba-roja de Túria Valencia 39.476761, -0.564086

2.4 Assembly routing

Once decided the location and understood the meaning of the different modules, it is the time to find the logical sequence for their assembly. Please note, this is another relevant challenge for three main reasons:

1) there are physical and logical constraints for the sequence of the assembly of modules
2) the formula student racing cars have been moved to fully electric vehicles only in the last few years, implying a change in the main assembly steps with respect to internal combustion engine ones. Furthermore
3) the number of electric engines can be different in number, position and thus assembly constraints. INSIA team choose to use four different electric engines positioned one for each wheel.

Just to clarify, some years ago formula student racing cars arrived to the assembly station only with their chassis; after that, the engines and the exhausts where positioned. The body mounting was one of the last assembly operations.

Nowadays, with new rules and the implementation of fully electric vehicles internal combustion engines and exhausts pipes are not present anymore. Furthermore, thanks to the development of new high-performance materials such as the carbon fiber, the chassis of the car is lighter and lighter every year, and the previous mainly plastic "body" is actually part of the chassis too.

For this reason, it is impossible to mount it as one of the last operations like it was done in the previous years and it is treated as a standalone module.

Taking into account all the cited parameters, the proposed logical assembly operation in the right order is listed here:

1) Main hoop
2) High voltage wiring
3) Low voltage wiring
4) Brake line
5) Traction and transmission pack

6) Electronics
7) Cooling system
8) Pedal box
9) Steering system
10) Seat
11) Safety harness
12) Nose
13) Front suspensions
14) Rear suspensions
15) Front wing
16) Diffusor
17) Wheels
18) Lateral wings and pods
19) Rear wing

With such a sequence, neither physical nor logical constraints limiting the assembly operations should arise.

2.5 Production balance

Looking at the standard times as defined in the previous paragraphs, it is clear to note that they are very unbalanced. From theory, it is known that there are two main ways to balance the production:

1) to increase the number of workstations performing the same operation
2) to smooth the operations allocating part of them to a previous or next station to reach a balance in the single working stations times.

Analyzing the standard times provided, it is underlined a very big difference in between those. In fact, some are of the order of one hour, and other of few minutes. For this reason, to think to balance the production by means of a higher number of stations results in a too much diverging-converging assembly stations behavior.

To prove it, just think to take the average time needed to mount the rear wing (4 minutes, one of the shortest), and compare it with the one to assemble the front or the rear suspension by means of a single resource (75 minutes, the highest): their ratio will provide the necessity of introducing 18,75 (thus 19) working stations so that the assemble of the suspension does not represent a bottleneck in the assembly anymore. Of course, this is not acceptable.

For this reason, **the balance of production**, based on their average standard times and only for the 1000 units production, **is reached by means of levelling of the different operations into the previous or next station**.

The standard time on which all stations have been levelled is 40 minutes. Hereafter it is reported the list of the time intervals needed for the new logical routing operations.

	TIME [min]		
Name of the modules in the different stations	Min	Max	Avg
Main hoop and HV voltage wiring	35	37	36
LV wiring and brake line	30	45	37,5
Traction and transmission without electronics	30	45	37,5
Electronics and first cooling system part	30	40	35
End cooling system, and pedal box	35	45	40
Steering, seat, safety harness	32	48	40
Nose + Front suspension part 1	32	48	40
Front suspension part 2	30	45	37,5
Rear suspension part 1	30	45	37,5
Rear suspension part 2	30	45	37,5
Front wing, diffusor, wheels and rear and lateral wings + quality check at the end of the line [15 min]	34	42	38

The result is 11 (eleven) stations with a smoothed average operation time of more or less 40 minutes. This is in line with the previous assumptions related to both number of stations and time scattering.

To reach this result, a consistent number of assumptions have been taken. Hereafter, they are reported for each of the station.

Station modules involved in the assembly	**Assumptions**
Main hoop + HV voltage wiring	“Monocoque” module is done of main hoop and nose. The nose cannot be mounted here because of the need to put pedal box, steering rack and others before to close the front part of the vehicle. High voltage wirings are assembled after. The same person takes the 4 groups and assemble them on the car.
LV wiring + brake line	While high voltage wirings are made of 4 mounting groups, low voltage ones are a unique set of cables to be assembled on the car. Other assumptions are not needed.
Traction + transmission without electronics	Traction, transmission and electronics were in the same initial module. Here are shifted to allow time levelling.
Electronics + first cooling system part 1	In this station, the first big halving of one of the main modules is performed. In fact, the cooling system is divided into two parts, one representing tubes and one the fun group. The time is supposed to be the same for both submodules.
Cooling system part 2 + pedal box	End of the cooling system assembly.
Steering + seat + safety harness	Interior elements mounting. No important assumptions are needed.
Nose + Front suspension part 1	The nose is mounted only at the end of the assembly of the modules regarding the internal part of the vehicle. This is a physical constraint. In the following, Front suspensions assembly is divided in two operations. Basically, the left suspension is mounted in one station and the right one in the next step.
Front suspension part 2	End of front suspensions assembly.
Rear suspension part 1	Same assumptions done for the front suspensions are used thanks to the similar layout.
Rear suspension part 2	Same of front suspensions part 2.
Front wing + diffusor + lateral pods + wheels + rear wing.	Here, aerodynamics devices are assembled to the racing car. Diffusor,

Quality check at the end of the line [15 min]	front wing and lateral pods are jointed when the car is on the line, before the wheels. After that, wheels and rear wing are assembled. This due to ergonomics reasons. Assembly quality checks of 15 minutes are done at the end of the line.

2.6 Production layout types and decision

The next step is the decision related to the production layout, meaning the way machines or assembly stations are positioned on the work area. Please note that this is not correlated with the logical sequence of the operations, but to the way these single operations are performed.

From the theory, it is known that there are mainly two opposite possibilities:

1) to make move the resources (thus the employees) around a **fixed-assembly position** workstation, where the product (here, the car) is kept always in the same position from the first step up to the final one. This kind of assembly layout is very common for huge works, like airplanes assembly. Moreover, it is widely used in handicraft production, where the final product is produced in few units. **This is the case of the formula student racing car production up to this moment**. In such a way, a very limited floor area is exploited and thus the space required is limited.

On the other hand, the material handling process required in this configuration is rather complicated. In fact, the physical flow followed by each component can intersect others, thus creating problems for the streamlining of the logistics operation. This last sentence underlines the need, in an always increased and standardized production like ours, to define a layout the most streamlined possible, with no or few physical flows crossing points.

Other more detailed reasons will be explained in the following dedicated comparison paragraph.

2) The solution to the previous problem, is the second possibility for the assembly stations layout too. Clearly, in this configuration, workers are fixed to their assembly station and

it is the product to move along a line. This configuration can be called "**fixed (paced) assembly line**".

Of course, many different kinds of assembly lines exist. Mainly, the difference is given by the product the line has to assemble. Is it easy to note the difference between the assembly of a small product like chip, and the assembly of way heavier and bigger product like, for instance, a quad. In some way, our assembly operations can be compared to the ones of a quad assembly. In fact, the dimensions and the weight are similar. What makes the difference in between the two previously mentioned lines is the material handling equipment.

For our purpose, a conveyor-type line will be implemented: the racing car cannot be moved on its wheels up to the latest operations, like mounting of aerodynamic devices and testing. Please note the term "paced" has been put inside brackets. This choice is given by the fact that usually, the line is thought to have a closed pace for repetitive work of the order of minutes, no more.

In this project, the pace is very slow and of the order of tens of minutes. Thus, **line is chosen due to the room and the weight of the product** mainly.

3) A third assembly layout is present. It is called "**assembly shops or not constrained assembly line**" and results in the utilization of different stations positioned depending from the operational logical sequence. The main difference with respect to the pure paced assembly line is given by its converging-diverging behavior that many times can be present. Here, like already discussed in the previous chapters when talking of the levelling of workstations times, this behavior would be so strong that is completely not recommended.

Moreover, it would go completely against the work done for the levelling and streamlining of the operations. Furthermore, this layout usually does not include a device able to move such a weight without problems. Always remind this project is done for a small-size competition car.

For our purpose, an **assembly line** is chosen.

As it is clear from the theory, many assembly lines can be present to satisfy the demand, if it results necessary. In this case, the time needed to assemble a car is more or less of one shift and given the fact one thousand complete assembled cars are required per year and 260 working days with two shifts each are present, **two parallel assembly lines are needed**.

Now, by making simple assumptions for the positioning of receiving and shipping warehouses, a first very rough scheme of the macro area of the plant can be displayed.

Please note this sketch is the result of assumptions that will be displayed in the following chapters.

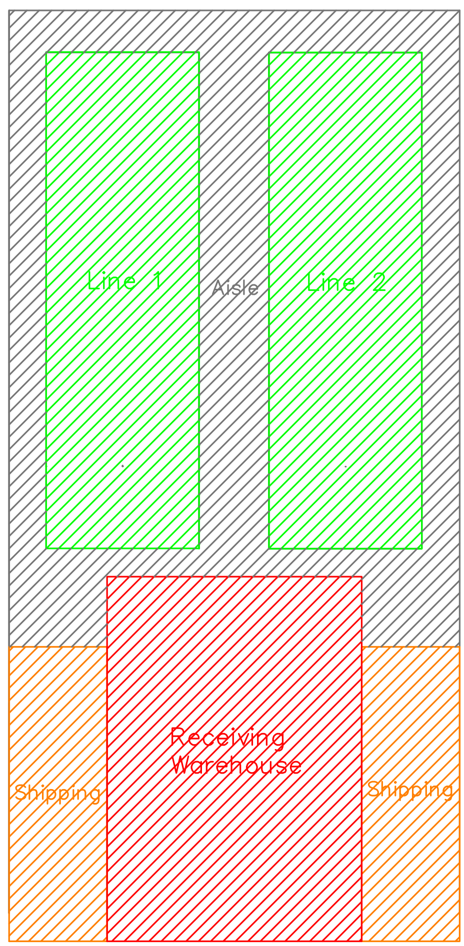


Figure 4 Main plant areas function allocation

Fixed position vs assembly line

This small digression is done **to highlight the reason why a fixed position layout is not worth for our purposes**. In fact, even though this thesis presents the intrinsic constraint of conjecturing a line as layout, for some aspects the fixed position could represent a valuable alternative.

The comparison is done with a configuration with just one fixed position station with 4 people working in. This layout, represents an alternative where the number of workers is consistently decreased with respect to the needed ones for the line, at least within a first analysis.

On the other hand, as it is clearly understandable, to think 4 workers can perform their relative assembly operations within the same station on a piece of relatively small dimension as it happens in their dedicated line stations represents an unrealistic hypothesis.

In fact, either considering all the 4 operators working at the same task, thus performing in an utopic best case the same operation at almost $\frac{1}{4}$ of the time required by the single worker, or considering 4 workers working with a dedicated assembly task, the linearity of the layout would be completely lost and the time can suffer a consistent increase.

As a matter of fact, in the first situation, it is unfeasible to assume the time to be exactly $\frac{1}{4}$ the initial one, because few modules have a number of items that can be managed by 4 workers without losses of time. At the same manner, logical and physical constraint to perform 4 different operations in the meantime would be significant.

In addition, when thinking at the reduced number of workers, it should be underlined the saving is related to the operational stations. In fact, the increased material crossflow, that would anyhow generate confusion in the assembly station, requires a huge increase of the work done by warehouse operators. De facto, it would be unrealistic to work with complete pallets of different items close to the station and break bulk operations should be done much more times than needed during the week.

At the end, the before mentioned saving does not result large. Thereby, the contained economical saving in manpower and initial investment does not represent a good solution for the long term.

Eventually, this choice would go against whatever assembly operation technological evolution required by the core issue this thesis is born from. Please note the mathematical proof about operating workforce will be discussed in the chapter concerning the workers evaluations.

2.7 Material Handling

This large part of the project deals with the very wide world of **material handling**. In fact, "material handling" is the movement, protection, storage and control of materials and products throughout manufacturing, warehousing, distribution, disposal and consumption[2].

As it seems clear, material handling too requires a consistent amount of assumptions for both the warehouses and the movement of material along the assembly line. This section will exploit the knowledge of previous Master of Science courses to set up the correct layout trying to optimize both the investment required for the handling devices and their utilization.

Carton boxes and wooden pallets

The first important choice to be made is the one related to the basic transport unit. Basically, a given type of casing is chosen such that each module is transported along the entire supply chain up to the line, where it is later assembled to the main racing car body, without occurring in any damage.

The casing material has to be able to damp out the highest number of shocks occurring during transport and handling. On the other hand, the massive utilization of such a casing requires to optimize the cost of those too.

For the above-mentioned reasons, it is better to opt for simple **carton boxes with polystyrene interior coatings**. Carton boxes represent the most used kind of transport unit in the industry and it is employed for many reasons. First of all, it is quite cheap. Please remind that when talking of very high unit numbers, a small unit cost saving can represent a way more important one on the total material handling cost.

Moreover, the polystyrene coatings usually present interior small channels, where products are positioned in, to avoid the last ones to be bounced inside the transport unit. In such a way, possible idle components avoid to touch each other during transportation and handling. Moreover, the polystyrene itself represent a very good quality to cost compromise to dump out shocks and filter vibrations.

In the following table, the dimensions of the boxes are reported for each module. These choices have been made possible thanks to the disposition of the drawings from INSIA institute, from which maximum dimensions of the components have been extrapolated. For privacy reasons, these drawings will not be shown in this project.

	MAXIMUM DIMENSIONS			
Name of the module	**Width**	**Length**	**Height**	**Carton box Y/N**
Main hoop	750	1180	430	Y
Nose	400	465	380	Y
HV wirings (rear + front same box)	1650	160	80	Y
LV wiring	1650	60	60	Y
Traction and transmission	1130	705	360	Y
Cooling system PART 1	360	350	220	Y
Cooling system PART 2	400	110	110	Y
Pedal box	365	300	340	Y
Steering	295	490	185	Y
Seat	890	660	700	NO
Safety harness	400	200	100	Y
Front suspensions PART 1	360	220	100	Y
Front suspensions PART 2	340	110	135	Y
Rear Suspension PART 1	380	220	100	Y
Rear Suspension PART 2	340	110	135	Y
Front Wing	1390	495	255	Y
Diffusor	1400	1440	240	NO
Wheel	510	510	270	NO
Lateral pods	900	485	420	Y (2 per box)
Rear Wing	1050	740	650	Y

This analysis results in the use of carton boxes for all but 3 modules, that are seat, the diffusor and the wheels respectively. For what concerns diffusor and seat the reason is found in their dimensions. In fact, such big products enclosed in carton boxes would result in the so called "air-shipping". With this term, in logistics, it is indicated the situation where the shape and the dimensions of a given product do not allow to exploit the space inside a closed box. For this reason, other shipment methods are used rather than the regular carton box.

For instance, it would be nice to exploit the repetitive shape of the seat and diffusor to ship them in piles with soft dividers whose task is to avoid the single elements to touch or wear during transportation.

On the other hand, the module "wheel" is not shipped in carton boxes for obvious reasons. As it happens many times, wheels are shipped wrapped by a plastic film either on pallets or not, depending upon their quantity.

For project purposes, all the elements will be shipped on pallets of different dimensions. In fact, the next problem to be overcome is the definition of the transport tools used to sustain the carton boxes. Indeed, it is clear carton boxes cannot be moved by forklifts or similar devices without the use of **pallets**.

Pallets exist of many materials like wood, plastic and metal. They can be bought of different standardized or customized dimensions and have many relevant properties. First of all, their ability to be moved by forklifts. Moreover, pallets allow more carton boxes to the accumulated on the same transport unit and thus to be moved all in one. Furthermore, pallets are durable components and can be reused many times before to be wasted. Last but not the least, many of them are almost 100% recyclable.

By analyzing costs and benefits, **wooden pallets are chosen**. In particular, EUR-pallet will be used. EUR-pallets are the classical wooden pallets used for transportation and are of standardized dimensions (1200 x 800 x 144 [mm]).

Figure 5 Wooden EURpallet example

Usually, for each of the modules, two controls are done:

- the first, related to its dimensions is aimed at understanding whether the given carton box requires a standardized or customized pallet dimension; The second, related to the admissible weight for the pallet, if one or more layers of products can be stored on each one. The admissible weight for a EUR-pallet is 1000 kg in not-uniform loading conditions. By just doing a rapid evaluation, it is known the average weight of completed assembled formula student cars is 200 kilograms;
- the second control does not represent a constraint for the project purposes. Thanks to this, only the analysis related to the box and pallets dimension is carried out for dimensioning aims.

This last analysis results in the following table, where the number of items per pallet is defined considering all the above-mentioned constraints.

Name of the module	Europallet Y/N	units/pallet
Main hoop	Y	3
Nose	Y	6
HV wirings (rear and front same box)	NO	60
LV wiring	NO	208
Traction and transmission	Y	4
Cooling system PART 1	Y	24
Cooling system PART 2	Y	126
Pedal box	Y	24
Steering	Y	20
Seat	Y	4
Safety harness	Y	120
Front suspensions PART 1	Y	90
Front suspensions PART 2	Y	147
Rear Suspension PART 1	Y	90
Rear Suspension PART 2	Y	147
Front Wing	NO	8
Diffusor	NO	5
Wheel	Y	8
Lateral pods	Y	3
Rear Wing	Y	2

As a result, it is worth to note all but 4 modules use the EUR-pallet. This problem arises from their dimensions, that in some cases exceed the maximum dimension of the EUR-pallets.

Please note that while the number of boxes (when present) in one layer is bounded by the dimensions of the upper face of the pallet, the number of layers used has been dimensioned following a logic that will be addressed in the paragraph related to the warehousing. Anyhow, the maximum height of the pallet and the products piled on it never exceeds 1500 mm.

Please note the previous discussion has been made for modules handling. For this reason, it is important to note that the **main body of the racing car**, is not considered inside the definition of modules. As discussed above, it represents the main element all the modules are jointed to during the process. Its dimensions and room are way bigger than all the listed modules. Thus, it needs a dedicated discussion about its transportation.

The main racing car body it transported on a wooden pallet too, without any kind of carton box, but just wrapped by a recyclable and partially recycled plastic film to avoid the wearing of whatever part during transport. This film is than taken away at the beginning of the assembly line along with the pallet.

It is necessary to say that in this case just one item for each pallet is brought, without any kind of piling up. The pallet cannot be a EUR-pallet due to the bigger dimensions of the racing car body. For this purpose, pallets of 2300 x 660 x 144 dimensions are used.

Receiving Storage

When talking of the receiving storage, it is required to define mainly four important characteristics:

1) The type of storage system and extension
2) The number of docks and container
3) The type and number of material handling means

Storage system

Starting from the **storage system** definition, it is known many different types of storage systems are present in the industry. Just to cite ones, it can space from very simple storage systems like on-the-ground pallet positioning or classical rack systems, to gravity-flow rack ones.

Please note the fundamental parameters that are taken into account to this purpose are the **moving frequency**, the **cost of the system** and the **selectivity index**.

The selectivity index, in a multiple product codes warehouse, is defined as the ratio between the number of directly accessible product codes over the total number of stored product codes and represents one of the major driving parameters for the decisions about the storage systems.

$$Selectivity\ index = \frac{\#\ directly\ accesible\ product\ codes}{total\ \#\ of\ product\ codes\ in\ the\ warehouse}$$

Another relevant index to analyze the performance of the warehouse is the so called “storage space utilization ratio”. With this term, two different ratios are identified. The first, called R_s, expresses the percentage of available floor area used to store the products with a given system and can usually be evaluated from a simple top view of the storage layout.

$$R_s = \frac{storage\ space\ floor\ area\ [m^2]}{total\ available\ floor\ area\ dedicated\ to\ storage\ function\ [m^2]}$$

The second, called R_v, expresses as a percentage the utilization of the cubic storage space ratio, basically, the volume. Here in, the height exploited to design the layout plays an important role.

$$R_v = \frac{cubic\ space\ storage\ capacity\ [m^3]}{total\ available\ cubic\ space\ dedicated\ to\ storage\ function\ [m^3]}$$

Here after, a list of the main systems is reported along with their most relevant characteristics. A picture for each of those is used to help understand the physical layout. Please note, each one of the following storage systems is implemented under a **roof-covered area** of the industrial building. This remark is done to highlight the difference with others systems, similar in their layout but exposed to weather and wearing because of their allocation in a not roof-covered area.

Stacks. No equipment is needed, stackable unit loads. It is simple and reconfigurable. High utilization of storage capacity ratios, usually has a selectivity index lower than 1. Very low investment cost.

Figure 6 Example of stacks inside industrial building

Traditional Rack Storage. It is a stacking frame for pallets and containers, whose selectivity is equal to 1. It has no picking constraints but affect forklift decision. Thus, decisions about aisle size and space utilization ratios are affected. It can be a one-side rack or two sides rack.

Figure 7 Tradition racks inside industrial building

Drive-in / Drive-through. It is a stacking frame for pallets stored by their wide side. The drive-in system is loaded and unloaded from the same side, following a last in-first out (LIFO) logic, while the drive-through is loaded and unloaded from opposite sides, this time following a first in- first out (FIFO) logic. The space utilization can reach 100%, but the height constraint is 6-7 meters. It is suitable for many unit loads of a limited number of product codes.

Figure 8 Drive-in racks inside warehouse

Gravity flow racks. They are also called "live storage". Equipped with roller conveyors with a slope ranging in between 3/4 %. Length limited to 18 meters as maximum, height up to 10 meters. Also, here, very high space utilization. It represents a FIFO mode. Selectivity can reach 100% but it is an expensive system.

Figure 9 Gravity flow racks example

Please note that, as always, the receiving storage follows a **break-bulk logic**. The break-bulk logic is the one where items are received in groups, usually on pallets, whose breaking is performed moving toward the assembly line. In fact, the need for the worker is to take the single product stored inside the carton box, itself grouped with others on the transport unit (in our case the pallet).

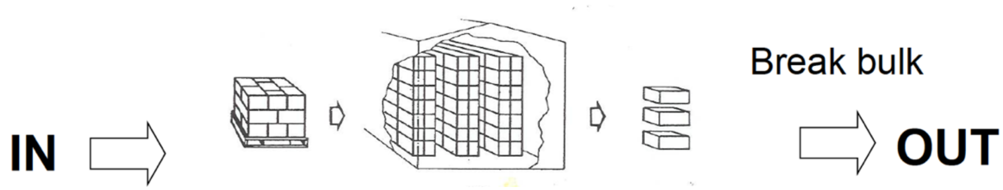


Figure 10 Representation of the break-bulk logic

Coming up to a point for the project, the number of product codes that are present in the receiving storage is conditioned both from the number of modules as defined in the previous chapter and the way in which the mounting of the different modules has been split.

This means, if a module like the front suspension is mounted in two consecutive stations, it makes no sense to have the front suspension pieces all in one box. To actively perform this kind of analysis at the moment of the design stage can be very useful to avoid wasting time for transportation of components from one assembly station to the next one.

For this reason, a **total number of different product codes equal to 23** is needed. Of these, 22 are of the car components while 1 is represented by the car body. The definition of each of them divided by the 11 stations is reported in the table of next page.

Station #	Product codes	Tot prod codes
1	1 monocoque, 1 high voltage wiring	2
2	1 low voltage wiring, 1 brake line	2
3	1 traction and transmission	1
4	1 electronics, 1 cooling system part 1	2
5	1 cooling system part 2, 1 pedal box	2
6	1 steering, 1 seat, 1 safety harness	3
7	1 nose, 1 front suspension part 1	2
8	1 front suspension part 2	1
9	1 rear suspension part 1	1
10	1 rear suspension part 2	1
11	1 front wing, 1 diffusor, 1 wheel, 1 rear wing, 1 lateral wing	5
		22

Moreover, without going deeply in detail with the numbers, the **moving frequency** seems to be **low**. Just think at the number of cars produced in one day.

This means, following the optic of a lower investment for the plant construction and equipment, that the choice for the storage system can space from simple stacks to traditional racks, each one with their own pros and cons.

At the end, **traditional rack systems** have been chosen for **all the 22 car components** due to the consistent number of product codes, even though the moving frequency is very low.

On the other hand, **stacks are used to store the car bodies**. The idea is to equip the pallets with a stackable system to increase the cubic exploitation of the plant and to provide a selectivity index equal to 1 without an excessive investment for the structure.

This choice is in line with the so called "ABC classification" of the different storage systems, where all of them are positioned in a grid depending upon product codes quantity and moving frequency. The grid is reported below.

<table>
<tr><td>A
Few codes
Large Q</td><td colspan="2">Stack
Drive-in</td><td>Stack
Gravity flow</td><td>Gravity flow w/
picking trucks</td></tr>
<tr><td rowspan="2">B</td><td>Moveable</td><td>Trad. racks w/
trilateral
sideloaders</td><td>Gravity flow</td><td rowspan="3">Trad. racks w/
picking trucks</td></tr>
<tr><td>Drive-in</td><td>Gravity flow</td><td>Trad. racks w/
trilateral
sideloaders</td></tr>
<tr><td>C
Lots of codes
Small Q</td><td>Moveable
Trad. racks</td><td colspan="2">Trad. racks or AS/R</td></tr>
<tr><td>Quantity / Moving Frequency</td><td>C
Low frequency</td><td>B</td><td>A
high</td><td>A/B/C</td></tr>
</table>

[41]

Figure 11 ABC classification

The **dimensioning of the traditional rack system** follows a detailed logic. First of all, it is necessary to define the number of pallets required to cover a given amount of production days. For our purposes, it is chosen to dimension the receiving storage to host a number of pallets able to sustain the production of **5 working days** (1 week).

The following table shows the number of pallets needed to supply the line for 5 days for each of the modules.

Name of the module	Units needed	Pallets expired	Rounded up
Main hoop	20	6,7	7
Nose	20	3,3	4
HV wirings (rear and front same box)	40	0,7	1
LV wiring	20	0,1	1
Traction and transmission	20	5	5
Cooling system PART 1	20	0,8	1
Cooling system PART 2	20	0,2	1
Pedal box	20	0,8	1
Steering	20	1	1
Seat	20	5	5
Safety harness	20	0,2	1
Front suspensions PART 1	40	0,4	1
Front suspensions PART 2	40	0,3	1
Rear Suspension PART 1	40	0,4	1
Rear Suspension PART 2	40	0,3	1
Front Wing	20	2,5	3
Diffusor	20	4	4
Wheel	80	10	10
Lateral pods	20	6,7	7
Rear Wing	20	10	10

It is clear a consistent difference is present among them. In fact, some of the product codes require 10 pallets for week, while others less than the 10% of the number of items present in one single pallet.

For this reason, an important assumption is taken. In truth, the traditional rack system will be dimensioned to host the maximum number of pallets that could lay in the storage system at the same time considering a well-defined scheduling for material supply.

De facto, all the product codes expiring more than one pallet in one week will be ordered every week as a fixed-supply. The other product codes will be supplied every 4 weeks, in a number suitable to sustain the production of the final assembled car for the related amount of time. This choice has been done to optimize the filling of the container for logistics reasons and will be discussed in the following.

Name of the module	1 week pallets expire	4 weeks pallets supply	
Main hoop	7,00		
Nose	4,00		
HV wirings		3	
LV wiring		0	1
Traction and transmission	5,00		
Cooling system PART 1		4	
Cooling system PART 2		0	1
Pedal box		4	
Steering		4	
Seat	5,00		
Safety harness		0	1
Front suspensions PART 1		2	
Front suspensions PART 2		1	2
Rear Suspension PART 1		2	
Rear Suspension PART 2		1	2
Front Wing	3,00		
Diffusor	4,00		
Wheel	10,00		
Lateral pods	7,00		
Rear Wing	10,00		
	55,00	**21**	**26**
		min	**max**

From the above table, it results a number of 55 pallets is needed every week for the products expiring in a time lower than 5 working days. On the other hand, a variable total number of pallets between a minimum of 21 and a maximum of 26 is required every 4 weeks to supply products with a later due date. Hence, **the traditional rack system has to be dimensioned to host a total number of 81 pallets**.

After that, the physical dimensioning begins. In fact, the number of rows and columns that are required along with the base rack dimension is assumed. Then, the number of levels in the height is defined.

Last but not the least, the aisle dimension is defined. Please note aisle dimension in between racks is conditioned by forklifts choice and racks disposition. By supposing so for this project, it is needed to take into account the mayor building constraints.

In fact, one main aisle of 5 meters crossing the plant side to side (top to bottom) is required and thus the minimum distance between stacks and racks is defined. The final layout shows a total of 5 rows and 4 columns and each of them can be loaded or unloaded by one side only). Moreover, an aisle of 3 meters is considered all around the base layout and this has to be considered in the evaluations for warehouse indicators.

The top view size of the single traditional rack unit is equal to 3000 x 1200 mm. These dimensions are obtained by the pallet positioning inside stacks units plus an additional clearance of 200 mm at each side of the pallet. For the height, the same threshold used for box dimensioned is left: this, along with the pallet height of 144 mm, results in a maximum lot height of 1500 mm.

Please note each lot hosts 2 pallets. As an overall, **41 lots are needed**. For symmetry reasons, 40 of those are built, 20 for each layer with 2 layers in the height. The last pallet can be positioned at the end of the aisle to avoid build a dedicated system just for it.

The floor space required for the traditional rack storage layout is equal to 162 m^2 and provides a floor utilization ratio of 59.85%.

For what concerns **car bodies**, they are transported on customized dimensioned pallets whose main dimensions are following the ones of the car body. The kind of system that is used is the stacks. In particular, a stackable system is used to allow pallets to be positioned one on the other.

For this first dimensioning, only two layers are allowed. Moreover, to optimize the logistic of the plant, two stacks of 10 pallets each are created in front of the line to avoid further material crossflows. The dimension of the single lot for the stack is 2300 x 660 mm (length x width) with a height equal to 1000 mm. This last dimension is the result of the pallet height (144 mm), the car body height (715 mm) and the clearance left (149 mm).

Stacks are positioned closer to the lines with respect to the traditional racks for handling reasons. Indeed, these represent the heaviest components of the whole assembly.

By just analyzing the layout of the stacks along with the central aisle, the floor utilization is very high, equal to 72,44% and the overall floor area utilized is equal to 25,15 m^2.

The scheme of the receiving storage tradition racks and racing car bodies dedicated area is reported here after.

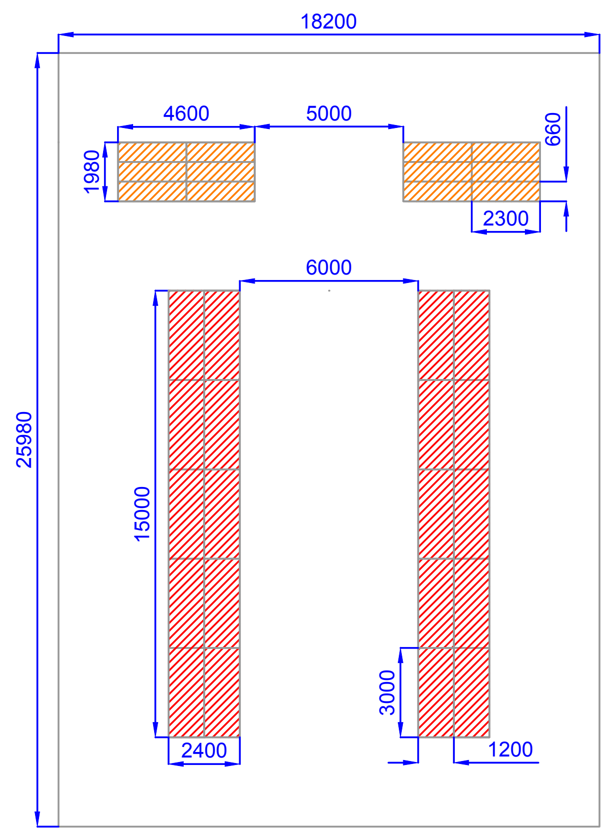


Figure 12 Design of receiving storage area and its dimensions

Eventually, analyzing **the characteristics of the receiving storage systems as a whole** considering all the additional aisle that round the base layout and the free space making part of the warehouse too, they result in a total floor extension of 472,84 m^2 and a surface utilization ratio equal to 19,08%. This result is of course provided by the consistent number of aisles, lowering the cited indicator.

However, taking off the main aisles and the space for docks, not belonging to the main warehouse, thus not considered in the evaluation of the **real surface utilization ratio**, results change as follows: the surface utilization ratio is **34.21%** and the **effective surface extension is 263.74 m^2**.

The **storage capacity**, simply defined as the maximum number of stored unit loads, is equal to 101 pallets.

At this point, one last check has to be done to evaluate the goodness of the layout and it is called "**Floor load capacity**". The floor load capacity is defined as the maximum weight a floor is engineered to support. In the U.S., the floor load capacity is given in pounds per square meter and an average value for regular industrial building floors is usually 500 PSF, thus 2500 kg/m^2 more or less. The task of the designer is to evaluate the maximum load per meter square in the warehouse layout and to check it to be lower than the floor load capacity.

In this project, the maximum weight per meter square holds in the receiving storage, where two layers of traditional racks host pallets of different shape with a maximum weight of 500 kg. At this point, given the dimensions of the pallets, the check is easy:

- The maximum load per meter square is 1042 kg/m^2
- The floor load capacity considered is 2500 kg/m^2

And given that $1042 \leq 2500$ the check result negative and the layout is finally confirmed.

Receiving docks and containers

At this point, the industrial building theory tells it is necessary to proceed with the evaluation of the number of docks and the decision about the type of containers. The choice of forklifts is a logical consequence that considers the type of storing system too.

First, some basic theory is introduced:

Dock. A loading dock (also called "loading bay") is an area of a building where goods vehicles are loaded and unloaded. They are commonly found on commercial and industrial building, and warehouses in particular. Loading docks may be exterior of fully enclosed. They are part of a facility's service or utility infrastructure, typically providing direct access to staging areas, storage rooms and freight elevators.

Figure 13 Industrial dock internal view

Figure 14 Industrial dock external view

Shipping container. A shipping container is a container with strength suitable to withstand shipment, storage and handling. Shipping containers range from large reusable steel boxes used for intermodal shipments to the ubiquitous corrugated boxes. In the international shipping language, "container" or "shipping container" is synonymous of "intermodal freight container", a container designed to be moved from one mode of transport to another without unloading and reloading.

The useful containers for hour purposes are divided in two families, depending upon their dimensions:

Twenty equivalent unit (TEU). A TEU is a shipping container whose internal dimensions measure about 20 feet long, 8 feet wide, and 8 feet tall. Usually it holds between 9 and 11 pallets, depending whether they are standard pallets or EUR-pallets. Two TEUs have the capacity of a single forty-feet equivalent unit (FEU).[2]

Figure 15 TEU container and dimensions

Forty equivalent unit (FEU). A FEU is a shipping container whose internal dimensions measure about 40 feet long, 8 feet wide, and 8 feet tall. It can hold between 20 and 24 pallets, again depending upon the kind of pallet considered. As it is clear, the changing dimension is the length. [3]

For the project, it is necessary to highlight a difference in between the general product codes and the car bodies. In fact, as already mentioned many times, general product codes are stored on traditional racks while car bodies on stacks. The two families are located in a different part of the plant even though they are not so far one from the other.

To optimize the layout, docks will be exclusively dedicated both to car bodies unloading and general components one. The dock for car bodies is positioned on the open side of the plant, the right one, and allows a direct communication with the committed storage area without crossing the area with traditional racks.

On the contrary, the two missing docks are located in the bottom part of the plant. Thus, **3 docks are present, 1 dedicated to car bodies and 2 for general product codes unloading**. These last two are located in the bottom part of the plant while the car bodies one on the right side. Their disposition will be clarified with the plant drawing in the dedicated chapter.

Please note the car bodies dock is positioned on the right side of the plant with the assumption of a **corner land area**, meaning trucks accessibility from the right side of the plant too. If this would not be possible for physical constraints, this dock would not exist and car bodies would be unloaded from the two main docks on the bottom side of the plant. **The width of the dock opening in the wall is of 2650 mm**, to fit the one of standard containers.

This choice is legitimated by the number of containers needed for transportation. **Car bodies and general product codes require 1 and from 4 to 6 TEUs respectively**. This last difference is given by the material receiving scheduling, that is created following the parameters discussed in the previous chapter and resulting in a not constant number of pallets for week. Of course, the number of TEUs needed is evaluated taking into account **dimensional constraints**.

Indeed, for what matters car bodies a maximum number of 3 layers is allowed, with no more than 9 units per layer. On the other hand, just one layer is allowed for the transport of other components. Luckily, this time two columns of pallets can be positioned on the same layer, resulting in a total number of pallets per truck equal to 14.

These docks present an inside building floor space that is exploited by workers to position the pallets provisionally before to be moved to their location in the real storage area. This choice is justified by its scope, meaning that in such a way a faster unloading of the trucks is performed. This alternative can produce a saving in the heating costs for the company, that avoiding the docks to remain open for twice the time, decreases heat dissipation especially during cold seasons.

In particular, the material is received at the end of the week to be ready to be used at the beginning of the next working day. More in detail, 4 hours of the second working shift of Friday afternoon are allocated because at that point the weekly production should be already saturated and workers can shift to a different task allowing for better resource utilization.

Just to have a clearer idea of the operating time, an average of 1 hour is considered to unload a TEU in dimensioning problem like this. Another hour is considered to store the pallets in their dedicated storage system. A total of two hours for each TEU is required to completely unload and store the received products.

However, thanks to a partial overlap of the scheduling, visible in the next plot, this operation will be completed in a total time ranging in between three and four hours, this time given by the fact that from 4 to 6 TEUs have to be unloaded depending upon the considered week and its relative receiving bills. White lines represent the weekly supply while yellow lines the one done every 4 weeks.

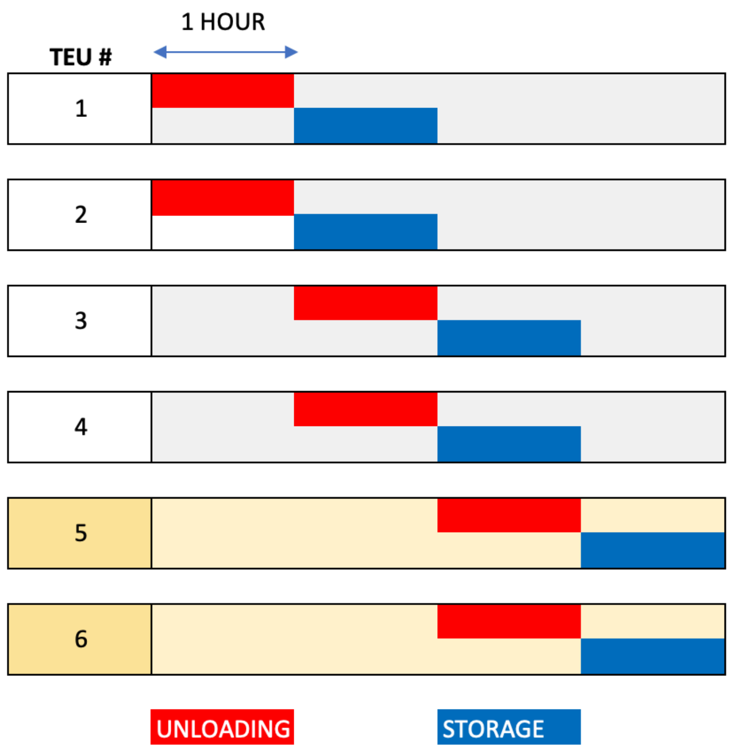


Figure 16 Unloading scheduling

Of course, for what deals with the car bodies, such a problem does not arise and the unloading operation is ended in 2 hours.

Material handling tools

The list of transport means from which the final option comes out is not too long in reality. This is due to the fact that the storage system layout for this project is not too complicated or technological. In fact, no side loaders or high reach elevators are needed. To clarify, the range varies into two basic alternatives:

Pallet jacks. This first family consists in a very wide range of alternatives with common characteristics. In fact, they are present on the market in many versions. The cheapest and most employed one is the so called "hand pallet jack".

Figure 17 Hand pallet jack

As the name suggests, it is a device used to manually move pallets (thus "transpallet") through a hydraulic lifting system. This category of tools usually needs a limited movement space and can be equipped with special implements, suitable for weighing or handling loads of irregular shapes. Pallet jacks lift the pallets from the ground of a minimum displace such that the weight can be moved.

Only the so called "high reach pallet jacks" are suitable to lift a weight from the ground of some meters.

Figure 18 High reach hand pallet jack

In this case, it is equipped with a special counterbalancing system needed to avoid the tilting of the structure. Usually, this system is implemented through a couple of arms that remain on the ground during lifting, so that to create the counterbalancing structure.

Last but not the least, “electrical pallet jacks” are mentioned. In this category falls all the pallet jacks implemented with an electric motor to put in action the hydraulic system.

Figure 19 Electrical pallet jack

Many times, these pallet jacks are equipped with a platform where the worker can step during the movement of the weights. By doing so, less time is needed either to unload a container or to move pallets from an initial position to a final one and speed up the process. Of course, these pallet jacks require an initial investment way higher than the hand pallet ones.

To sum up, these families of products could be very useful in a layout with stacks as storage system and a single-layer loading of containers. Indeed, in a configuration with multilayer storage like traditional racks or double loading layer inside containers, they basically lose their usefulness.

To counteract to this drawback, another family of means is introduced:

Fork trucks. Fork trucks are widely employed inside industrial buildings and they present a larger range of alternatives with respect to the pallet jacks. De facto, inside the definition of “fork trucks family”, many subgroups are present.

Traditional fork trucks are also called **counterbalanced forklifts**. Generally, a counterbalanced forklift presents four wheels, of which two bigger and two smaller; a cabin, where the driver can seat and is protected by an overhead guard; an hydraulic system, itself composed by a mast, defined as the upright structure where another part of the system, called carriage, can move up and down thanks to a system powered by a lifting chain; the forks are attached to the carriage, thus they move with it. The operator can activate the lifting system by means of the mast operating leverage. The must can swing.

A picture indicating the different sections and components of the system is reported below:

Figure 20 Fork truck component description

Moreover, under the seat of the operator, there is the engine compartment. The forklift can be powered either by an electric or an internal combustion engine. In the first case, it can be used both inside and outside a closed industrial building. In the second case, it can be used only outside due to its pollutant emissions.

Anyhow, the positioning of the engine compartment in that specific location has been studied to act as a counterbalancing weight for the lifted pallet: in fact, both the internal combustion engine and the battery packs weigh sufficiently to act as mentioned.

Technical specifications distinguish the different kind of forklifts. In fact, when choosing among alternatives, capacity, maximum weight, dimensions, minimum aisle width and so on have to be analyzed. A list of the different parameters and standard alternatives is reported:

Q	Capacity	kg	**600**	**1.000**	**1.600**	**2.000**	**2.500**	**3.000**
P	Weight	kg	1.500	2.500	3.000	4.000	4.500	4.900
I	Lenght of truck, w/o forks	mm	1.300	1.800	1.900	2.000	2.200	2.400
L	Total lenght of truck	mm	2.100	2.800	3.000	3.000	3.200	3.400
m	Distance b/w forks and front wheels	mm	220	330	350	440	440	440
p	Wheel base	mm	860	1.100	1.500	1.530	1.530	1.600
H	Max lift	mm	3.600	3.300	3.300	3.300	3.300	3.300
R	Min radius of curvature	mm	1100/1500 (3)	1400/1700 (3)	1500/1900 (3)	1.900 (4)	1.950 (4)	2.100 (4)
W	Minimum aisle width	mm	1800/2300 (3)	2900/3100 (3)	3.500 (4)	3.500 (4)	3.600 (4)	3.700 (4)
	Max speed loaded/unloaded -Movement	m/s	3/3,2	3/3,2	4,1/4,4	4,1/4,4	4,1/4,4	3,9/4,4
	- Lifting	m/s	0,3/0,45	0,3/0,45	0,4/0,55	0,4/0,55	0,45/,06	0,44/0,6

Nevertheless, a special mention is required for the characteristic of **Carrying Capacity**. The Carrying Capacity is somehow more difficult to be evaluated with respect to the Load Capacity, meaning the maximum load that can be lifted by the forklift, and it is defined as:

$$C = Q * I$$

$Q = load\ carried\ by\ the\ forklift\ (\leq Load\ Capacity)$

$I = distance\ between\ the\ load\ center\ of\ gravity\ and\ the\ axle\ of\ the\ front\ wheels$

$(A + B, \quad see\ next\ picture)$

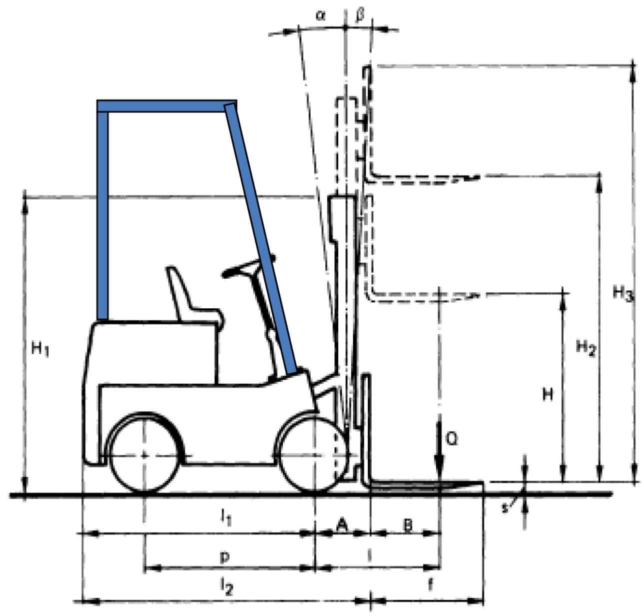


Figure 21 Forklift main dimension

Carrying and Load capacities show a mutual dependence. From the theory,

$$Carrying\ Capacity = f(H_{forks}\ ; L_{forks})$$

where the dependence from the forks' height (H_{forks}) and the forks length (L_{forks}) is shown. Next diagram and its arrows help to understand how to exploit these correlations by means of a plot.

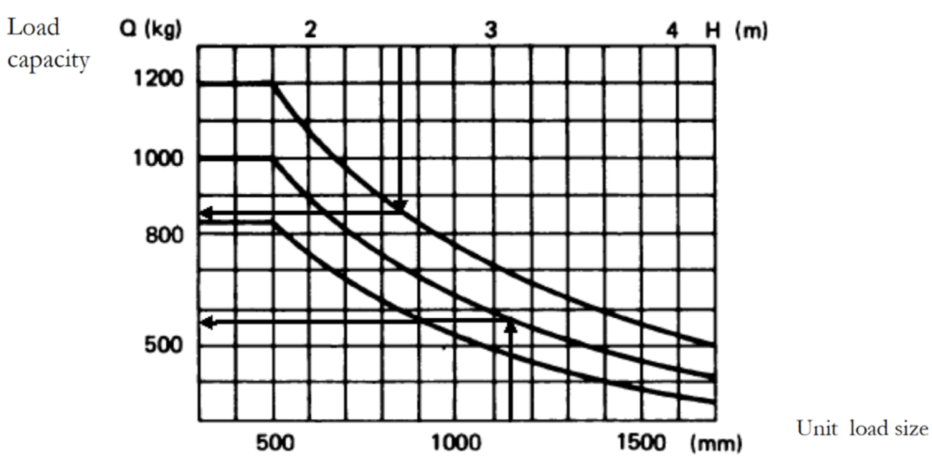


Figure 22 Carrying capacity plot

To move one, other subfamilies of fork trucks can be cited and each of them has special characteristics that differ from the ones of the traditional counterbalanced forklift. From the literature there are:

- **Narrow aisle trucks**, where the operator stands up to save aisle and steering space on a platform similar to the one of electric pallet jacks. They can be equipped with a reach truck actioned through a scissor shaped device that is useful to reach pallets at given distance with respect to the mast. Of course, the Loading Capacity is generally lower with respect to the traditional forklifts.

Figure 23 Narrow aisle truck later view

Figure 24 Narrow aisle truck front view

- **Sideloaders**, **bi-lateral** or **tri-lateral**. They can shift on the sides to save space in store rooms, obtaining a reduced aisle width compared to the one needed for forklifts with retractable mast. Usually, they have a high lifting up to 13-14 meters, but the cabin of the operator cannot be lifted too.

  They are equipped with a system that allows to choose the picking height for the forks and normally they are driven either by floor-installed rails or underfloor magnetic strips.

Other families could be cited but, given their uselessness for the project aims, the theoretical dissertation is over here. To come to a point, **traditional counterbalanced forklifts are chosen** for this project. This choice is justified by many reasons. In order:

- the storage system that is used in the industrial building is either stacks or traditional racks. This supposes to have more levels of storages, self-eliminating the possibility of exploit pallet jacks for both systems.
- the production sustained by the plant is not so high and thus its warehouse does not have to hold a consistent number of items. Of course, this is one of the reasons why the floor extension is relatively small and can justify the use of 3 meters wide aisle for the regular forklifts instead of narrow aisle forklifts or sideloaders.
- traditional forklifts are cheaper than other more technological or particular subfamilies, like the ones cited above.

Eventually, traditional counterbalanced forklifts with electric engine, will be used for all the pallets movements inside the plant. This meaning:

- from the container to the receiving buffer area
- from the receiving buffer area to the receiving storage
- from the receiving storage to the assembly line

The last point will be treated in detail in the following paragraphs.

An example of counterbalanced forklift powered by an electric engine is the one showed in the picture. It is of the FBC23N – FBC30LN cushion tire forklift series by Mitsubishi Forklift Trucks manufacturer, with a loading capacity in between 2000-3000 kg.

Figure 25 Example of electric counterbalanced forklift

For what concerns the number of forklifts bought for the plant during this first stage of design, it is necessary to refer to both the container unloading scheduling and the moving frequency to from the receiving storage to the line floor area.

For project purposes, the main constraint is represented by trucks unloading, because it is done at a specified time of the week all in one allocating time that otherwise would be lost.

Having a look to the scheduling, it is clear a maximum number of **5 forklifts** is working in the same time. Thus, the initial number of bought electric counterbalanced forklifts is 5. Those ones, when not working, are recharged in the battery charge room, that will be located in the main plant layout.

Assembly line tools and handling

Now, it is time to shift this dissertation on what concerns the assembly line material handling. When talking of this, it is clear the focus should go basically on two main aspects: first, the way the car is moved along the line considering ergonomics too and then, how workstations are supplied and their basic layout.

The line layout

Starting from the very basic design, it is needed to recall the kind of assembly layout that has been chosen. It was the so called "fixed paced assembly line". Again, in this case it is excessive to define our rate a "pace". In fact, normally this term is used to indicate an assembly line with standard times of some seconds.

In our case, as already discussed, the workstation time is on average of 40 minutes. Moreover, it is shown from the literature and from next scheme, that assembly lines are usually implemented for a very high demand per year, something different to the analyzed case.

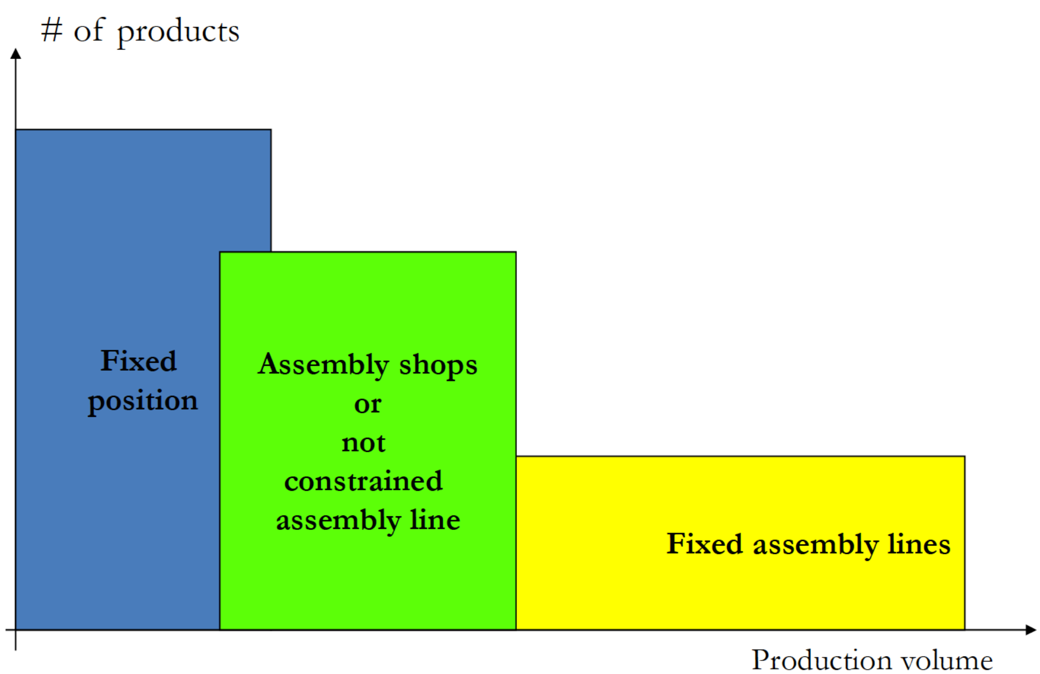


Figure 26 Assembly layout decision plot

Strictly following the previous plot, for the accounted market demand, the best solution would be either a fixed position assembly layout or an assembly shop. To clarify, the line has been chosen because of an implementation required by the project itself. This meaning that the studied business case, requires the fulfillment of an assembly line as a prerogative.

What is done here, is to justify this choice and to optimize its design in order to legitimize the required initial investment. De facto, a whatever assembly line even though not so technological, represents a higher investment than a fixed position assembly configuration.

The logical reasons bringing the decision to move toward the line one are related to the weight of the racing car and its roominess, that do not allow operators to move the car from one station to next one by hand or anyhow alone. In fact, it is supposed to have **one operator working for each station** and to have at least for people moving a huge weight results impossible also from an ergonomic point of view.

Moreover, thanks to the chosen configuration, many crossflows of materials are avoided. In fact, it is better disposed to streamline the flows of material rather than a fixed position assembly station.

To come to a point, the dimensions of the assembled racing car are similar to the ones of a quad, for this reason, a line similar to the one of their production or assembly plant is taken as reference.

Examples of assembly lines of Honda and Suzuki manufacturers are reported below to allow for a clearer mental visualization.

Figure 27 Honda manufacturing line (1)

In this picture, coming from the Honda manufacturer institutional demonstrative video related to their quad assembly plant, it is shown the part of the assembly where the quad is on its wheels yet. Thus, it is closer to the end of the assembly. Undoubtedly, this is not the regular situation along the line.

In fact, the assembly of the wheels both in this project and in quad assembly is performed in one of the last stations. In the previous steps, the car is sustained by clamps and a central mounting system that upholds the work body to allow the worker to perform his job properly with the smallest number of physical barriers possible.

In the next picture a line with the following characteristics is shown. This time, it comes from the Suzuki institutional video.

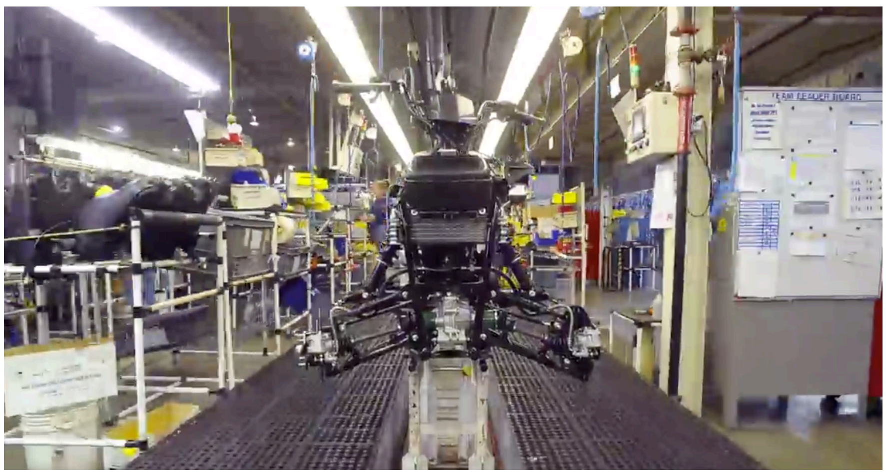


Figure 28 Honda manufacturing line (2)

As it is clear, the quad moves on the central conveyor and the workers are able to step on the lateral dark gray grid to make their tasks.

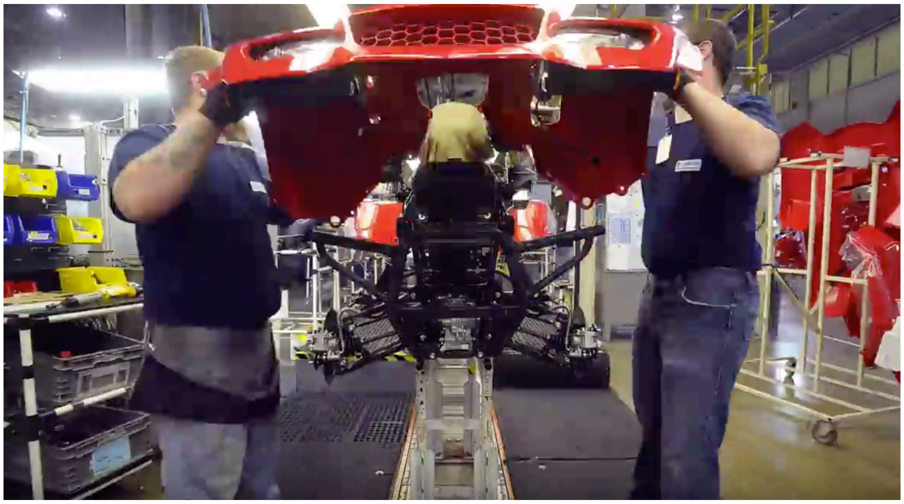


Figure 29 Honda manufacturing line (3)

The assembled racing car shows another similitude with the quad. In fact, some tools like the diffusor have to be mounted on the underbody of the car. To maintain always the same height for the operator working area and thus of the line goes against the basic ergonomic principles. That is the reason why the line for the racing car assembly is thought to be equipped with leverages to rotate the car body in the needed stations once a given position is reached. This operation is performed thanks to devices actioned by the workers.

In such a way, the laborer avoids unnatural body positions that could result in physical diseases. As a matter of fact, without going deeply in detail in the problem, there are regulations governing the different movements the worker cannot do at all or that can repeat few times during its shift.

For instance, leaning back or stooping toward an object at a low height is an operation that can create serious problem to the spine, in particular when done during the lift or release or consistent loads. For this reason, ergonomics devices like the chairless chair represented in the following picture are used to reduce the physical discomfort.

Anyhow, those are very expensive and are not considered for our purposes.

Figure 30 Ergonomic tool for industrial plant

The type of conveyor that is chosen is the **overhead rail conveyor**. This kind of device is present in the market in two subfamilies, the **monorail trolley conveyor** and the **bi-rail trolley one**. As names suggest, the difference in between the two is basically given by the number of rails present in their design.

As a matter of fact, many similarities are present. In fact, in both layouts, the motion is transmitted by means of a chain attached to brackets, themselves moving thanks to two wheels running on the internal surface of a double T profiled rail. The very big difference in between the two is the continuity of the motion of the bottom part, named trolley, that in the monorail configuration cannot be detached contrary to what happens in the bi-rail one.

For this reason, the bi-rail configuration is chosen. A scheme with the names of the main parts is reported hereafter.

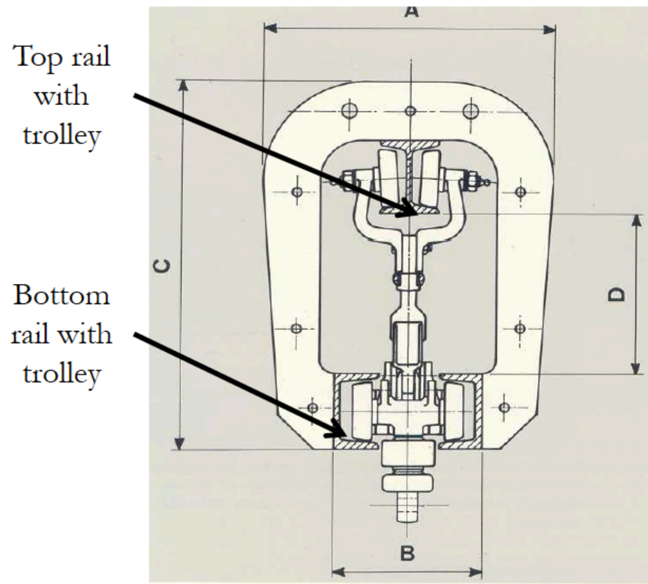


Figure 31 Bi-rail overhead conveyor scheme and rails indication

Of course, some specifications have to be added. In fact, as already mentioned, the car body needs to be rotated when underbody components are added to its assembly.

This operation is manually actioned by workers thanks to leverages, and it is possible owing to the attachment of the car to the conveyor, provided by means of four bushing, two for each side of the vehicle, opportunely distributed along the length of the body.

This is possible thanks to the light structure of the car, ranging in between 180-200 kg on average for the whole assembled car. As it will be clearer from the final drawing, the shape of the conveyor results almost elliptical thanks to the disposition of the assembly stations.

At the end, this results in an opportune solution because other possibilities, like the **chain tow-conveyor**, would require a consistent increase of the needed floor space such as an encumbrance for workers that could just move on one of its sides. With such a layout, either twice the overall number of stations would be required in terms of moving plates or a mirroring of the assembly line stations of one of the two lines would be necessary.

In the first case, the linearity of the material flow will be maintained requiring a huge investment at the beginning. In the second one, an increase of the material handling means would be the result of the lost line layout, because assembled cars would require to be transported in the final warehouse in some ways. Thus, the initial investment saving that could arise by choosing this cheaper type of conveyor does not represent a real source of rescue.

Workstation feeding

The second relevant topic to be analyzed is related to the workstation feeding. **Workstation feeding** represents the set of operations that are performed to move the material to the desired workstation with an appropriate procedure and following a time schedule so that the proper material is at the disposal of the operator when needed without creating any kind of delay in the production or assembly operations.

In simpler words and for the project purposes, this field includes:

- the way the material is picked up from the receiving warehouse and brought to the desired workstation in time
- how the different equipment and semi-finished products are grouped and positioned in the workstation area

For the first problem, that deals with material transportations, it is worth to recall the way modules are stored. In fact, modules arrive in the receiving warehouse on pallets and they are stored without any brake-bulk operations. The last ones, are performed when the pallet reaches the workstation because of lack of the selected product code.

This choice has been taken in order to face the need of the minimization of the initial investment. Indeed, by doing so, the number of forklifts needed for the overall amount of operations is reduced with respect to a possible configuration with brake-bulk operations performed in the warehouse. In this way, a streamlining of the single workstation would be surely obtained, but at least a dedicated resource, being it an automated conveyor or a workman, should be dedicated to feed the line stations.

In fact, another topic that will be treated in the following is the one of workforce, that is relevant from an economical point of view in whatever business case.

At the end, it results that the same regular counterbalanced forklifts used to unload the trucks are used to feed the workstations. This is given by the fact that the overall utilization of the present material handling resources is basically low and their use for other purposes allows for a better investment depreciation.

Please note this choice is in line with the aim of the project, thus the minimization of the investment without falling into an impairment of the efficiency of the assembly line. Just in case of future investments and increase of production, the logic can change and the way stations are fed too.

Now, it is possible to evaluate the final number of forklifts that is always equal to 5. Indeed, it is not necessary to buy other fork trucks, because containers are unloaded on Friday afternoons while the line is fed before the start of the first shift of the following working week.

The area for forklifts battery recharge is located both close to the receiving storage area and to the assembly floor area. This choice is justified by their utilization space, limited to the two before mentioned locations.

Workstation layout

Next topic touches one of the most critical design stage of the plant. At this point of the project, the first layout of the plant is already in place and it will be shown in the following. On the other hand, to complete the treatment of the line material handling topic, it is necessary to provide at least a rough scheme of the workstation.

As a matter of fact, the space where the worker can move in, is limited on the two sides. On one hand, the conveyor transporting the to-be-assembled car and the black areas where the worker can stand on; On the other hand, the station with tools and modules pallets where the worker can draw to perform his tasks.

An example of this layout is reported in the next picture, always deriving from the Suzuki quad assembly plant.

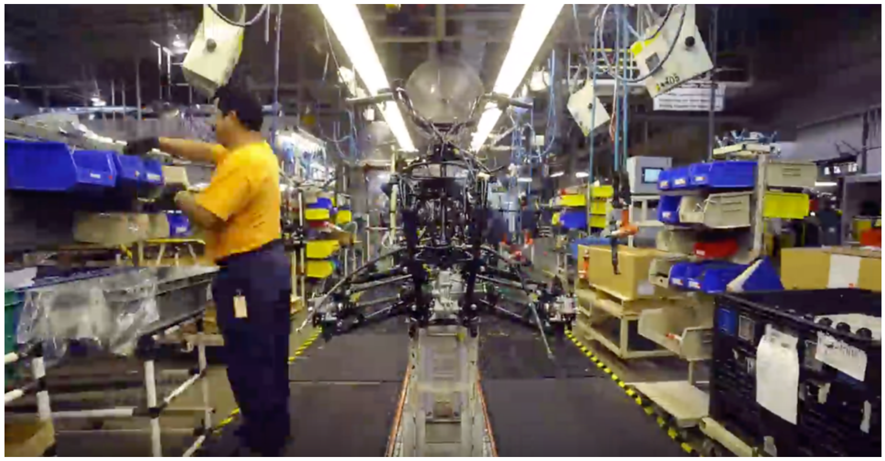


Figure 32 Honda manufacturing line (4)

Moreover, the pictures show other important details:

- the tools used for assembly are usually pending from overhead structures such as those ones used to help the worker handle bulky elements
- the integration of human resource and mechanical material handling equipment is optimized
- small size products like screws and nuts are stored into plastic boxes of different colors and dimensions, themselves located in inclined structures and positioned so that to avoid awkward movements for the employee
- small carton boxes, when present, are located on the same structures, this time equipped with gravity rollers so that it can be fed on one hand of the bin avoiding the dedicated resource to invade the working area, the last one representing a safety requirement too.

Figure 33 Industrial container for workstation

With the following top view, it is possible to visually understand the allocation of spaces to the various elements.

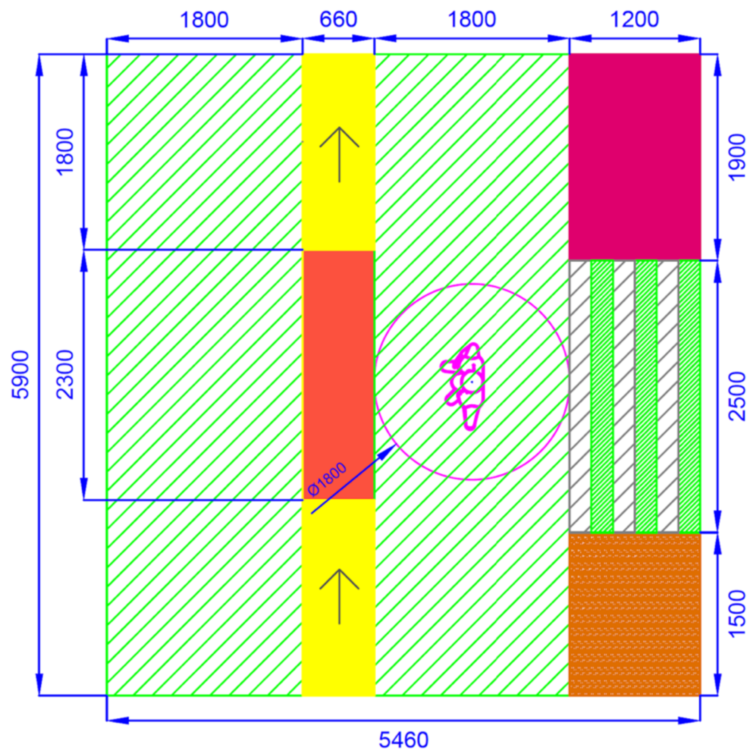


Figure 34 Assembly station repetitive unit

As it is clear from the CAD drawing the maximum dimensions of the repetitive unit sides are 5460 mm in the width and 5900 mm in the height. The dark pink central rectangle represents the position of the assembly line for the car body; The yellow ones the path followed by the overhead conveyor. The dashed green area constitutes the area where the worker, here represented in the top view by the violet person and its circle, can move and it is of a width of 1800 mm rounding up the car body working position. This dimension is the same of the worker moving area portraited by the violet circle.

On the right side, the tool bench, the pallet and the space for workers passage are determined. The wooden pallet is located in the bottom right corner while the tool bench in the upper right one.

This scheme is taken as a repetitive module for the design of all the stations expect the last one. Of course, with a higher level of details, relevant differences could arise.

In the station number 12, never cited before and with a different layout with respect to the other modules, the car is just unloaded from the conveyor and loaded on the pallet for shipping. The scheme is reported hereafter.

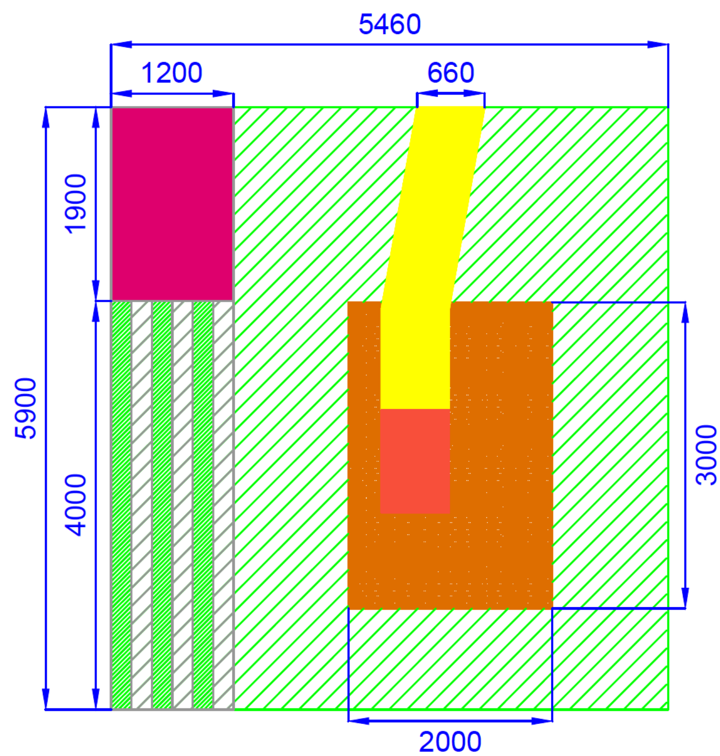


Figure 35 Final assembly unloading station design

In this case, the width of the aisle is larger because of the need to make pass the forklift and provide accessibility to the pallet.

Shipping Warehouse

As last point, the dimensioning of the shipping warehouse is performed. Please remind that at this time of the project we are dealing with a complete assembled car type of product and thus all the units should be shipped already on their wheels.

Unluckily, it is not like this because a relevant difference occurs in between regular vehicles chassis and the one of formula student racing cars.

In fact, the car body of the last ones is much more sensible to wearing than the ones of mass-produced vehicles and the vibrations or shocks coming from the road during transportation could seriously affect the quality of the final product. That is the reason why the final assembled car, after the quality checks, is **shipped on wooden pallets with dismounted wheels**, positioned on the sides of the car body. **The pallet dimension is** not standard but **customized** and it is of 2000 x 3000 mm as floor area with an encumbrance in the height of 1030 mm. **Soft inserts** are positioned in between car body and pallet to dump out the shocks deriving from transportation.

The end production warehouse

Considered what stated previously, for the final warehouse two main important decisions have to be taken and they are related to the type of stocking structure and the number of days of production the warehouse has to sustain to provide its maximum dimensions.

As a matter of fact, a reasonable number for the warehouse is to **sustain a production of 5 working days, mainly 20 units of final assembled cars**.

The type of storage system chosen is again the stacks but this time the layout is different with respect to the one of car bodies in the receiving storage area. In fact, given the flow of material inside the plant, the necessity of **splitting the final warehouse in two parts arises**.

Please note, this is not a problem because the structure is the simplest one and only requires a dedicated floor area, that could be converted in the future into whatever other facility operating or storage area.

To fit the slender layout of the plant, and provide the final 1:2 side to side optimal ratio, the single shipping warehouse is provided with 5 units in the length and 2 in the width with 1 layer in the height only: no particular stacking tools are required. A lateral aisle of 3 meters is assumed to the external side to let forklifts move easily. A rough scheme is reported hereafter.

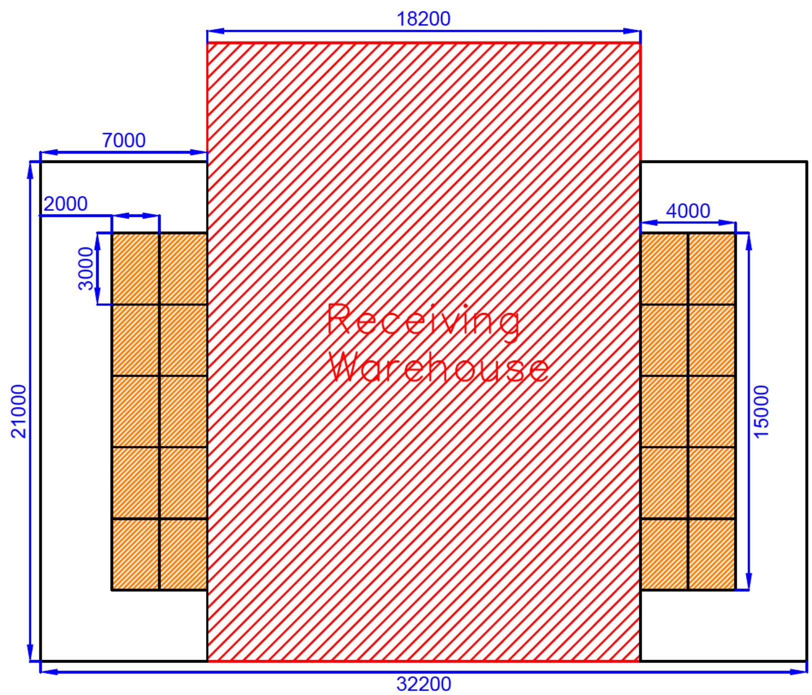


Figure 36 Shipping warehouse design

Here, the positioning of these two areas, at shipping warehouse sides, is very clear. The same holds for the dimensional constraints. Please note the inner aisle are not reported because they are present in the external part of the receiving storage area yet and these two zones in the reality would represent a continuous space.

By means of simple calculations is it evident the floor area extension with such a configuration is equal to 294 m^2 while the surface utilization ratio is equal to the 40,82%. Moreover, the maximum width of the two warehouses basically is the same of the production area, providing a slender layout overall.

The scope of the two free space area left in the upper part of the two-shipping warehouse are used for forklifts recharging area (on the left hand side) and for car bodies dock area (on the right hand side). These last two will be clarified in the final drawing present in the following pages.

Shipment logistics

When dealing with such a kind of final products mainly two types of transportation means are considered, and are:

- closed containers with one or two loading levels depending on the pallet encumbrance
- adapted car transported with multi loading levels (usually 2)

Unfortunately, this last type of transport mean cannot be used because requires cars to be on their wheels. As already discussed, this is not our case and thus the choice is the one of **regular container shipment**. Hence, the alternatives are either TEUs or FEUs.

Given the dimensions of the pallets and their positioning inside the two different types of containers it results in a total number of pallets per containers equal to:

- 6 for each TEU organized 3 for level and 2 levels
- 12 for each FEU organized 6 for level and 2 levels

Given the fact that for the receiving material only TEUs are used, those are chosen for this purpose too.

In fact, from a logistic point of view, the cost the company could sustain to require an external logistic operator container of the same type would be lower with respect to that of the mix of two containers of different dimensions.

For what concerns the number of containers used to transport the overall number of cars it is equal to 3,33 and thus **4 TEUs are required**.

As it happened for the receiving storage products unloading logistic operations like containers loading and unloading are performed all together in a specified time of the week. In this case, it is at the beginning of the following week and the reason why it is clear.

In fact, when talking of receiving products it makes sense to think to receive those ones when the storage is almost empty, but on the other hand, logistic companies are not working during the weekends thus cars cannot be transported to their destination.

Two docks are built for shipment. By considering a time of 30 minutes required to load a TEU with a relatively low number of pallets and that no scheduling is needed because no intermediate movement operations are performed, **the total time required to empty the final warehouse is equal to 1 hour**.

It is clear this is not the most efficient number of docks for the project, because just one could be enough. Unluckily, the disposition of the two wings of the shipping warehouses requires two docks, one for each wing.

Thanks to the previous assumptions an increase in the number of material handling equipment means is not required because only two forklifts are used for this operation.

Please note that at the end 4 docks are positioned on the bottom side of the plant and one on the right one. A part from the already mentioned constraint for the physical implementation of the right one, the 4 on the lower side are thought to be able to sustain a bigger production in the future.

Indeed, for the first-production loading and unloading operations, that are not done in the meanwhile, just 2 could be enough. In this case, the two docks would be positioned equally spaced from the main emergency exit and the left and right building walls.

2.8 Workforce evaluation

The following chapters define all the missing elements to complete the layout of the plant.

Hereafter, the number of workers needed to satisfy the current market demand is determined. This final amount is the result of the sum of all the blue and white collars.

First of all, one worker for each assembly station is assigned; Thus, having two assembly line of 11 stations each the total number of workers in the lines will be equal to 22.

For what concerns the human resources needed to load and unload the trucks they can be evaluated easily thanks to the work done before on the shipping and receiving scheduling.

In fact, from that, the number of workers employed in such operations is equal to the number of material handling transport means used in the meanwhile. Moreover, as already discussed above, these tasks can be performed by the same workers of the line that are free because of the end of the weekly production.

This decision allows for a better exploitation of workforce, that would otherwise be left free before the end of the shift given that no work is required anymore. The result is that **no further resources have to be hired for loading and unloading operations.**

On the other hand, given the reduced final size of the industrial building, just one person is taken both as lines and warehousing operations supervisor. Furthermore, one to two operators are paid to perform security guards at the main gates.

As a general rule, white collars are usually dimensioned to be equal to the 20% of the blue collars. Thus, they are 6 for this plant. At the end, a total number of employees equal to 56 is needed for the two shifts. Of these, 22 are lines operators for each shift (thus 44), 1 is warehouse and lines manager for shift (thus 2), 2 are security guards per shift (thus 4) and 6 are white collars.

Blue collars work with 2 shifts per day of 8 hours each, with a lunch break of 45 minutes. White collars follow the same scheduling but with just 1 shift per day.

Fixed position vs assembly line workers comparison

To conclude and to finally prove the saving in workforce would not be enough to justify a fixed position layout choice this paragraph focuses on **the evaluation of the line laborers only needed in the two layouts**.

Please note that the time required to complete the operations in the fixed position layout, considering the sources of delays mentioned before, is accounted with a multiplicative factor of 1,3 thus taking into consideration an average increase in time of 30%.

Furthermore, the number of laborers required due to the increased material handling operations is evaluated as the 30% of the workers in the workstations.

	LINE	FIXED POSITION
Unit average assembly time [h]	6,63	9,95
Available time in 1 year (with 2 shifts) [h]	3770	
Time needed to complete annual production [h]	6630	9945
Parallel layouts needed [lines or fixed positions]	2	3
Workers per shift	22	12
Total workers	44	24
Increase in material handling operators		8
Handling + workers	44	32

As it is clear, just a saving of 14 workers is obtained, not enough to justify the bulk of problem that would occur by adopting the fixed position layout.

2.9 Expansion areas

The expansion area in the theory of industrial building is an area of the plant covered with the roof that allows for future expansion of all the zones of the plant, being those either working areas or plant support functions.

It is mandatory to add this area in the first design of the plant to avoid future huge expenses: in fact, it is way more expensive to modify the plant layout once walls are positioned rather than to create empty areas where future lines or storage systems will be located.

As a matter of fact, the expansion area has to be present for whatever area of the building covered with the roof. In this case, given the straight vertical layout of the plant, it is **located on the left side of the plant**. In fact, given the presence of the installed dock on the right one, it results impossible to proceed with a right-handed expansion.

Please note this choice would not be correct if a different stacking system of the shipping warehouse would be used. In fact, in case of future expansion, the receiving warehouse should be expanded too and this is made possible by the fact that the shipping warehouse is realized of stacks only, without any kind of loaded structure that would require further disassembly operations. Indeed, both the receiving and the shipping areas can be expanded on the left-hand side.

The regular extension of the expansion area is normally evaluated as the 30% of the plant area covered with the roof. Thus, given the **total extension of the plant covered area equal to 2138,08 m^2** the expansion area is designed with a rectangular shape of sides 66,4 m in the height and 10 m in the width with an **overall extension of 664 m^2** (exactly the 30% of the previous mentioned covered area).

In the picture of next chapter, the expansion area is visible and represented with a brown color.

2.10 Final plant layout

The final layout of the plant is represented in the following pictures and it has been implemented with the Autodesk AUTOCAD software.

The **first drawing** is a scheme of the logical disposition of the different area of the plant, meaning lines and warehouse areas such as the expansion one. Main dimensions are reported to confirm the maximum area covered with the roof expansion. An external wall of 200 mm is reported to confirm its real disposition in the layout. Docks are reported in blue and have a width of 2650 mm to fit containers one.

The **second drawing** is more detailed and reports the scheme and disposition of the lines units. It is clearer the continuity of the overhead conveyor, in this way optimized with a continuous elliptical configuration. Dashed yellow area represents warehouse area, while grey one general aisles for forklifts maneuvers. Please note walkways are not represented to avoid draft overwhelming that, for our scope, has to markedly portray the lines and warehouses area.

The forklift recharging area is located in between lines and warehouse area on the top of the left-hand side of the shipping area. On the top of the right hand one, a maneuvering area is left for car bodies logistic operations. This blue dashed area can be used for temporary pallet positioning during unloading operations also.

In addition, it is evident the arrangement of the modules to create the two lines. In fact, both the right and the left ones have the first module as close as possible to the receiving warehouse while the last one is closer to the shipping area.

For the disposition of the cited area mentioned in the related chapter, the **two lines result mirrored** one to the other.

Another additional constraint is related to main aisles. In fact, the plant has to be crossed side to side by two 5 meters wide main aisles for safety reasons. This task is accomplished with the one separating the two lines, that continues in the receiving warehouse, and from the one crossing the plant from left to right between warehouse and assembly areas. The four ends are underlined in the drawing by the four pink docks while plant area is colored blue to highlight main aisles.

Another relevant aspect, out of the project purpose, is the positioning of the **offices**. Here, the suggestion is to **use mezzanine floors** to locate them. “Mezzanine” is a general term used for any raised platform surface intermediate floor.

Industrial mezzanines are typically free-standing steel structures installed with in a building. They can be used for virtually any type of application including storage, offices, production, manufacturing and observation platforms, because of their decking variety options including wood, Resindek, concrete, grating, and still to fit the various applications. Generally pre-fabricated, they require quite simple assembly operations to be performed on the site. [4] Even though our assembly units are quite light, because no CNC machines or similar are present on the floor area, these floors are thought to sustain only offices and lockers.

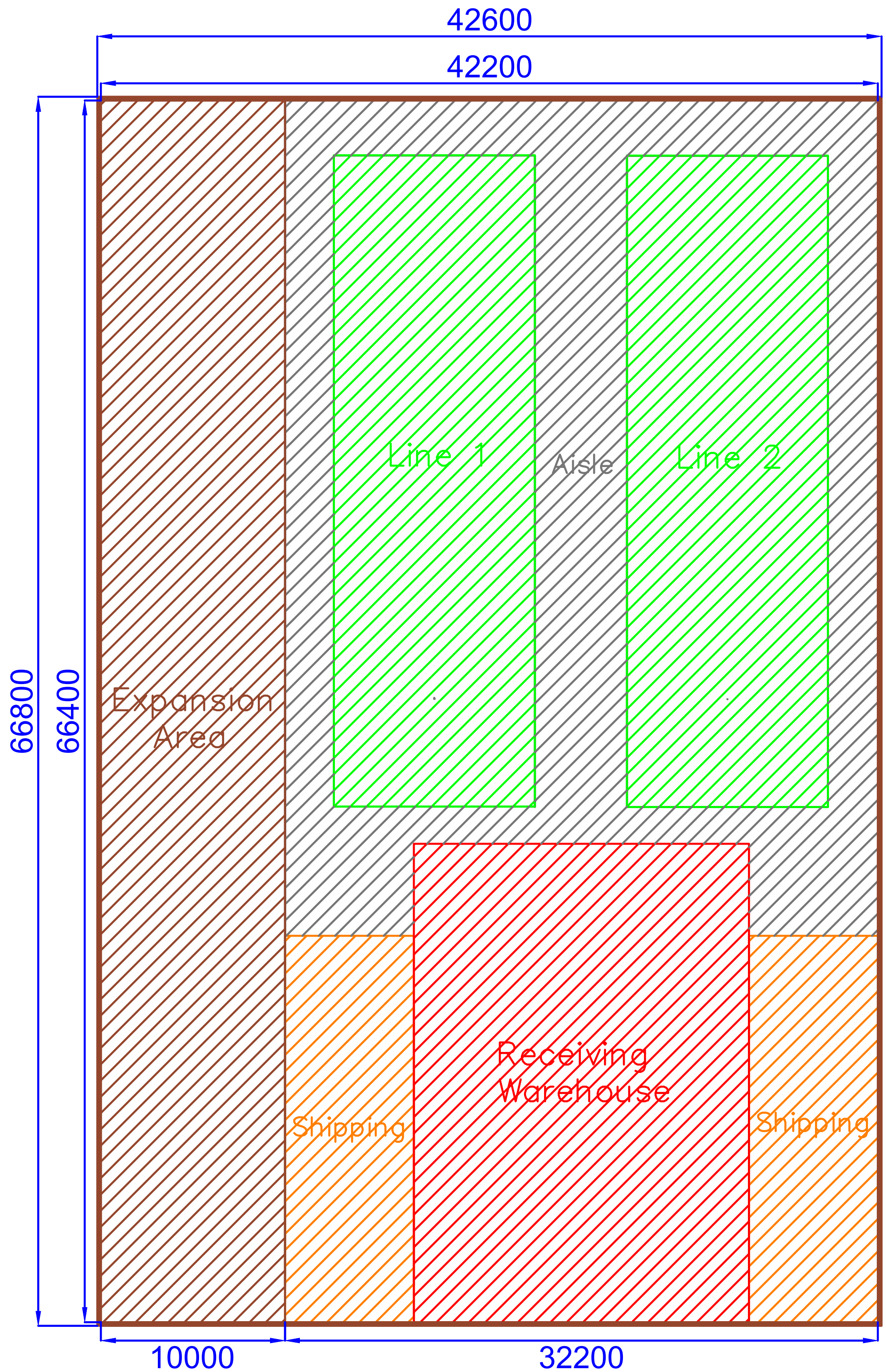
Moreover, they can be positioned almost everywhere because the **height below truss** of the building is neither completely exploited by warehouses nor by lines. In fact, the maximum height is reached by racks of receiving storage, with a value of 3 meters. The last one has to be compared with the general height below truss of industrial building, **ranging between 6 and 8 meters**; It is evident the space is enough to build remaining sectors.

Figure 37 Mezzanine floor

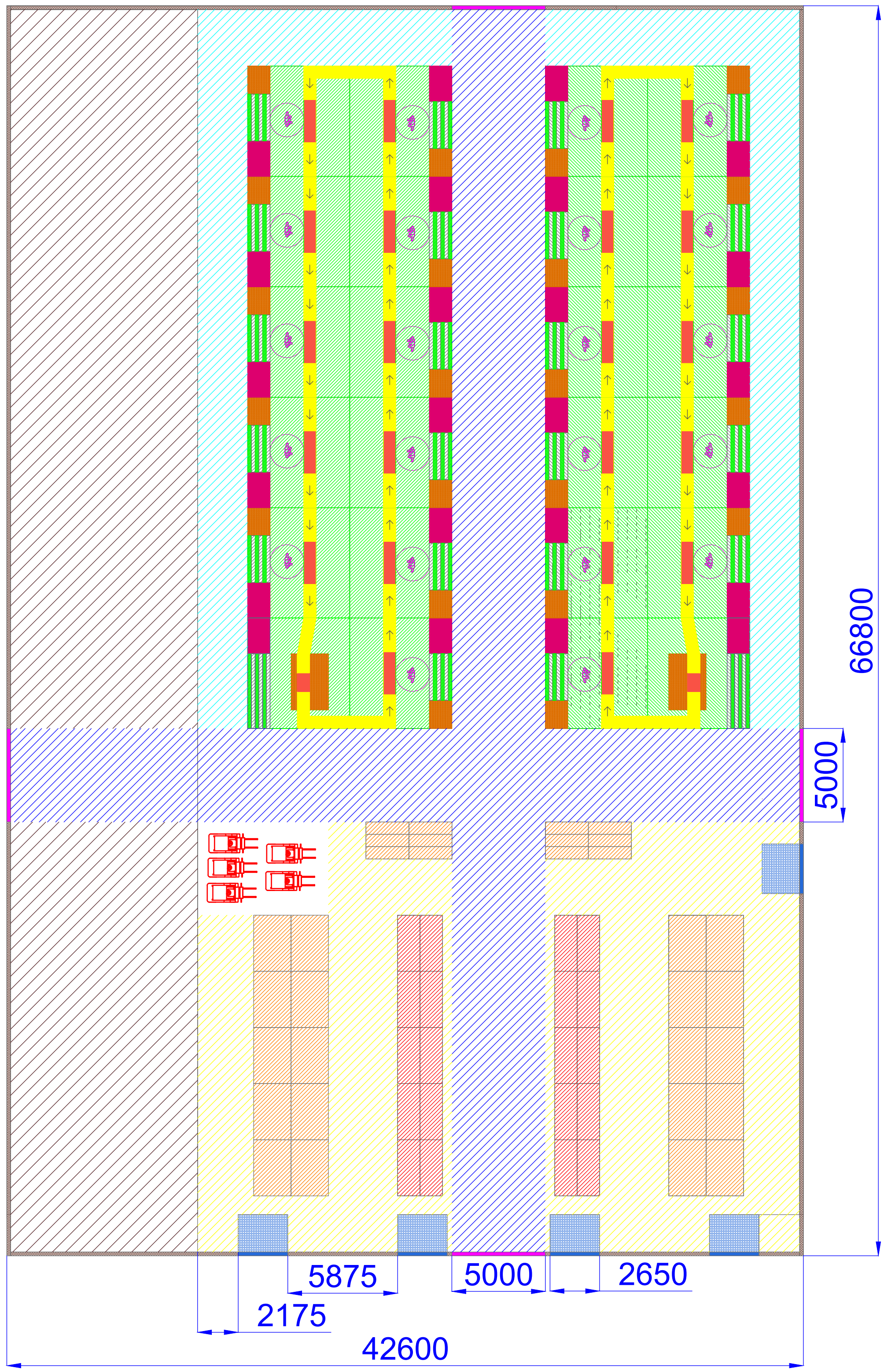
The choices about roof, pillar positioning and wall type, plant support functions are left to a next more detailed design phase, that could be addressed in the future starting from the work done up to this moment. The same holds for the masterplan and related concerns.

For sake of accuracy, it is mentioned that the first plant layout has been dimensioned in a flexible way to host different land characteristics. In fact, many times, constraints are coming from the available side of the plant area facing the street. The designed solution, along with the discussed characteristics, allows to either have a building facing the street on one side only (the docks one) or on more sides. The Valencian area taken as a land at the beginning of the dissertation, just represent an example.

Of course, to appreciate further details of the drawing it is recommended either to open the Autodesk AUTOCAD file or to refer to the A0 printed plot.



Drawing 1 Final allocation of plant area with expansion one



Drawing 2 Final preliminary working area plant layout and dimensions

3. Factory Physics approach

In this chapter, the theory concerning the **analytic analysis** for **line balancing** and **process variability** is introduced under the name of "Factory Physics approach". Unluckily, this precise method, **is very long to be applied and usually it is not used in companies**.

One of the purposes of the thesis is to exploit the power of Anylogic simulation software, able to provide precise outcomes and allow for a faster line validation and process variability analysis. Moreover, this whelming analysis represents a powerful tool when dealing with cycle times of the order of seconds, while the project one is of the order of dozens of minutes.

Anyhow, the theory behind the analytical method is reported for sake of completeness in the following. Please note, it will focus on the line rather than on the warehouse loading and unloading operations. These last ones, can be analyzed by means of others parameters, mainly cited in the previous chapter.

3.1 Production system and its parameters

In order to provide a deep insight of the following theory, some main definitions have to be introduced. These are relevant to provide a complete overview of the terms will be used in the following.

Production system. It is defined as a network of processes and stockpoints through which parts flow according to a defined goal. The network is composed of **routings**; Routings are composed of **processes**. The study of the manufacturing system focuses on the analysis of the network and the flows along the routings.

Workstation. A workstation is a collection of one or more identical machines.

Part. A workpiece, sub-assembly, assembly or component.

Raw material. It is defined as the material stocked at the beginning of the line.

End-item. It is the part sold to the customer.

Consumable. Generally, it is the material used in the process to allow workstation working.

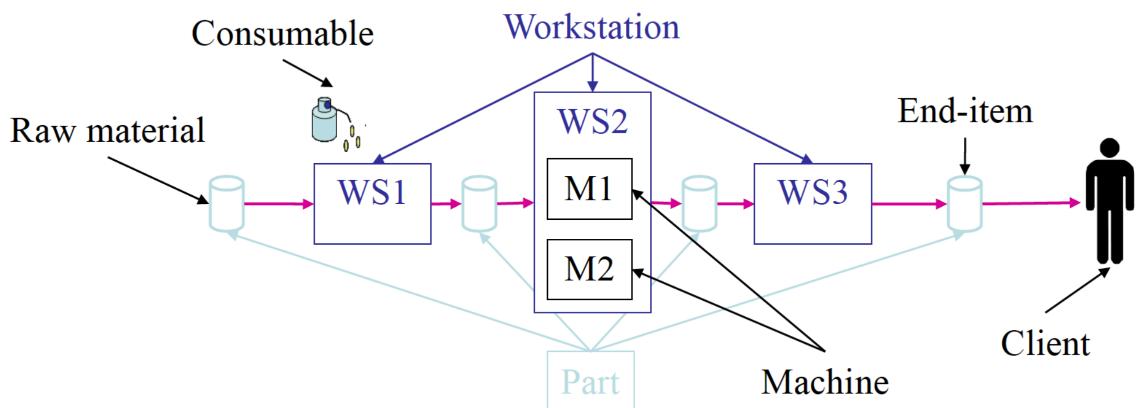


Figure 38 Production system and its part representation

Routing. Sequence of workstations a part passes through.

Order. Request for a defined end-item together with quantity and delivery date.

Job. It is the physical material flowing along the line.

Lead time (LT). It is the time available for the manufacturing of a part or a job in the line.

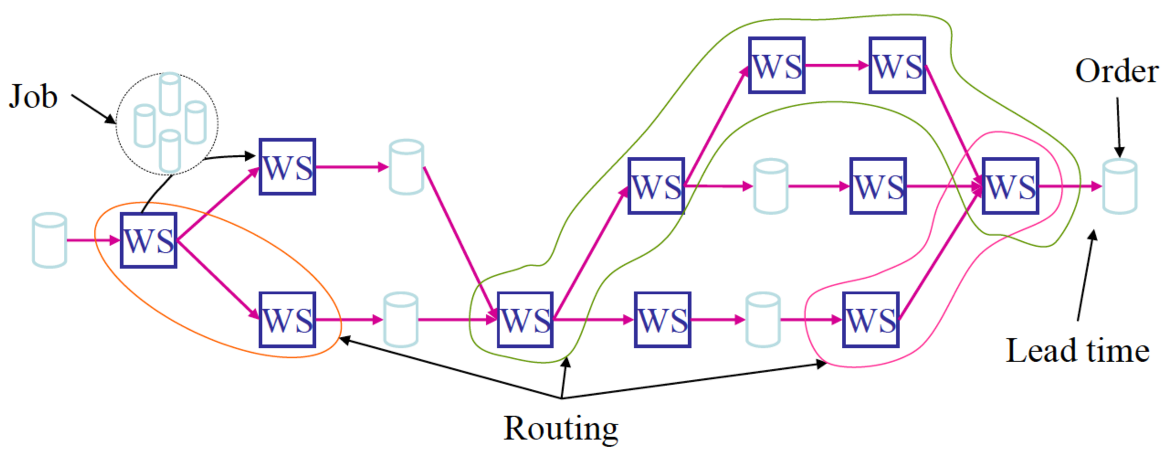


Figure 39 Routing, order, lead time and job graphical description

Throughput (TH). Average quantity of non-defective parts produced per unit of time.

Cycle time (CT). It is the mean time a part spends in the routing.

Work in process (WIP). It is the inventory in the routing.

Raw Material Inventory (RMI). Inventory at the beginning of the routing.

Finished goods Inventory (FGI). Inventory at the end of the routing.

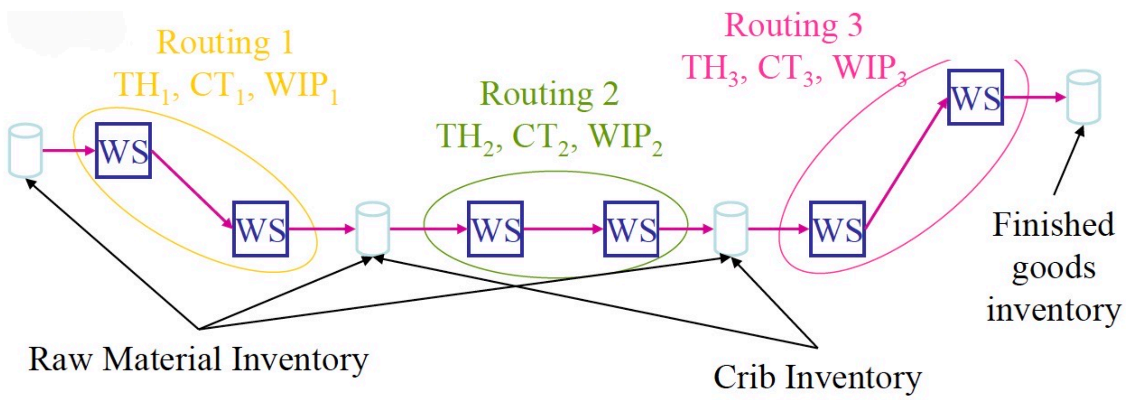


Figure 40 TH, CT, WIP, RMI and FGI graphical description

3.2 Workstation parameters

Now, focusing on the single workstation, the following **general** parameters can be defined:

- r_a = arrival rate of parts
- t_a = mean time between arrivals
- r_o = base production rate
- t_o = mean base production time
- r_d = departure rate
- t_d = mean time between departures.

Next picture helps understanding where to ideally allocate the mentioned parameters.

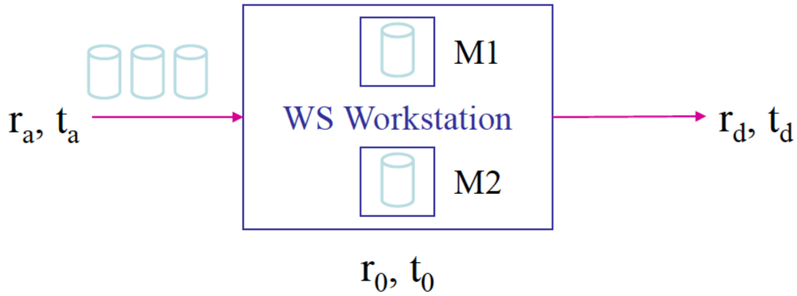


Figure 41 Workstation parameters

Each workstation can be characterized by a relevant parameter, called **utilization**, defined as the fraction of time a workstation is not idle for lack of parts. The utilization can be numerically evaluated as:

$$u = \frac{r_a}{r_o}$$

where both r_a and r_o have been defined previously.

It follow the introduction of the so-called **critical parameters**, so-called because they represent extreme cases of already mentioned parameters. Inside this family, there are:

Bottleneck rate $(\boldsymbol{r_b})$. It is the production rate of the workstation with the highest utilization.

Raw process time $(\boldsymbol{T_0})$. Sum of the mean effective process times of the workstations in a line.

Critical WIP $(\boldsymbol{W_0} = \boldsymbol{r_b} * \boldsymbol{T_0})$. It represents the level of WIP providing the maximum throughput and the minimum cycle time in a line without variability.

3.3 Little's Law and Benchmarking

In this section, it is analyzed the **correlation between** some of the **parameters** introduced in the two upper paragraphs. In particular, one of the most known laws in this field is the Little's one.

The **Little's Law** states that the work in process can be obtained as the product of the throughput and the cycle time. Thus meaning:

$$WIP = TH * CT$$

Of course, the WIP is measured in [parts], the TH in [parts/time] and the CT in [time].

Under this optic, the benchmarking is introduced. The **benchmarking** is the **evaluation of line performances** (thus WIP, TH and CT) **based on data gathered inside or outside the line**. De facto, all what treated in the following can be used as a line validation tool, thus not concerning a deep analysis of the workstation.

The benchmarking can either be **external** or **internal**. In the first case it is meant as a comparison of the collected data from two similar lines.

Please note this collection of data is not easy and many times lines could not be homogenous. In the second case, the measured line performances are compared to theoretical performances evaluated from a set of parameters. Improvements in the line could modify the theoretical performances.

Studies performed on the internal benchmarking result in three extreme cases, delimiting TH and CT operating areas. These three are called:

- **BEST CASE** : consists in the situation with **no line variability**.
- **WORST CASE** : represents the case of **largest deterministic variability**.
- **PRACTICAL WORST CASE** : meaning the case of **largest probabilistic variability**.

By means of simple analyzes the following results are obtained. Demonstrations will be omitted.

Best case

The TH linearly increases for values of the WIP up to the critical value W_0, remaining constant at the bottleneck rate r_b for higher values. Analytically:

$$TH_{best}(w) = \begin{cases} \frac{w}{T_0} & if\ w \leq W_0 \\ r_b & if\ w > W_0 \end{cases}$$

Moreover, the CT remains constant and equal to T_0 for values of the WIP not higher than the critical value W_0, linearly increasing for higher values. Analytically:

$$CT_{best}(w) = \begin{cases} T_0 & if\ w \leq W_0 \\ \dfrac{w}{r_b} & if\ w > W_0 \end{cases}$$

Worst case

The TH is constant for all values of WIP, while the CT linearly increases at a higher rate with respect to the one of the CT of the best case for values $w > W_0$. Thus:

$$TH_{worst}(w) = \frac{1}{T_0}$$

$$CT_{worst}(w) = w * T_0$$

Practical worst case

The largest random variability, representing the practical worst case, occurs when the possible status in the line show the same probability: balanced line, workstations composed of single machine, process time exponentially distributed.

Please remind the exponential distribution enjoys the so-called **memoryless property**, meaning that the knowledge on the time spent by a part in a certain workstation does not provide any info on the time the part will leave that workstation. The memoryless property can be analytically represented as:

$$P(X > t + s | X > t) = P(X > s)\ for\ s, t > 0$$

At the end, the CT will be function of w and shows both critical parameters T_0 and r_b. Thanks to the Little's law, the TH can be than obtained and it will result function of the same parameters. Please note TH shows w both at the numerator and denominator.

Starting from the evaluation of the average time on a given workstation i:

$$Ti_{avg} = \left(1 + \frac{w - 1}{N}\right) * t$$

The cycle time results:

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

While the throughput:

$$TH = \frac{WIP}{CT} = \frac{w}{W_0 + w - 1} * r_b$$

Three cases comparison

Eventually, plotting in function of WIP both TH and CT for all the three mentioned cases, it is possible to delimit a working area analytical results should fall in. In the next examples, the best case is represented in blue, the worst in pink and the practical worst one in yellow.

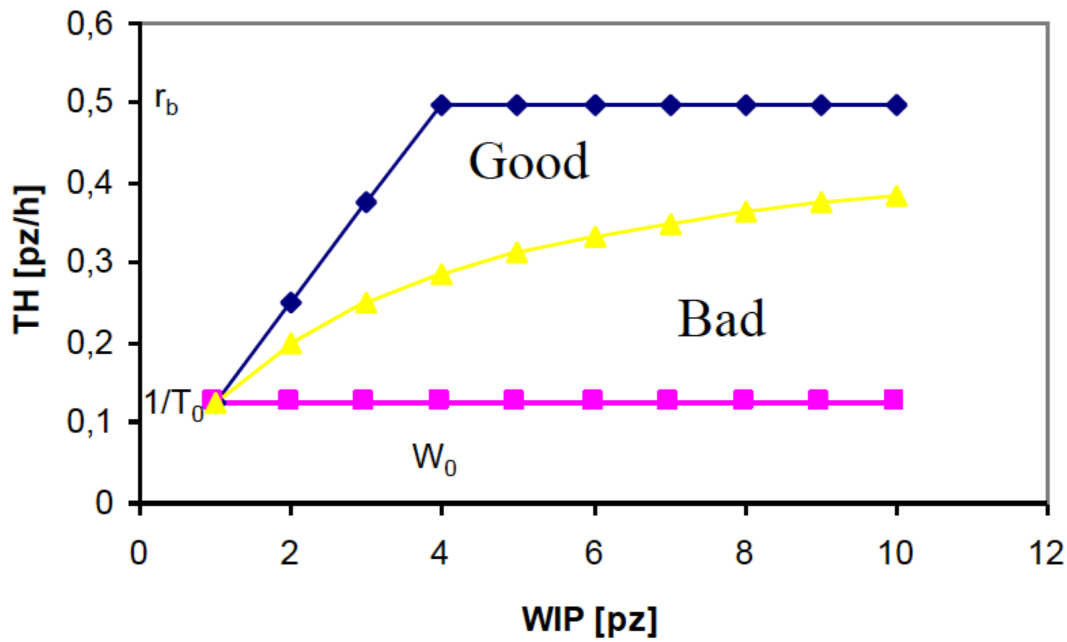


Figure 42 TH in function of WIP in the 3 cases

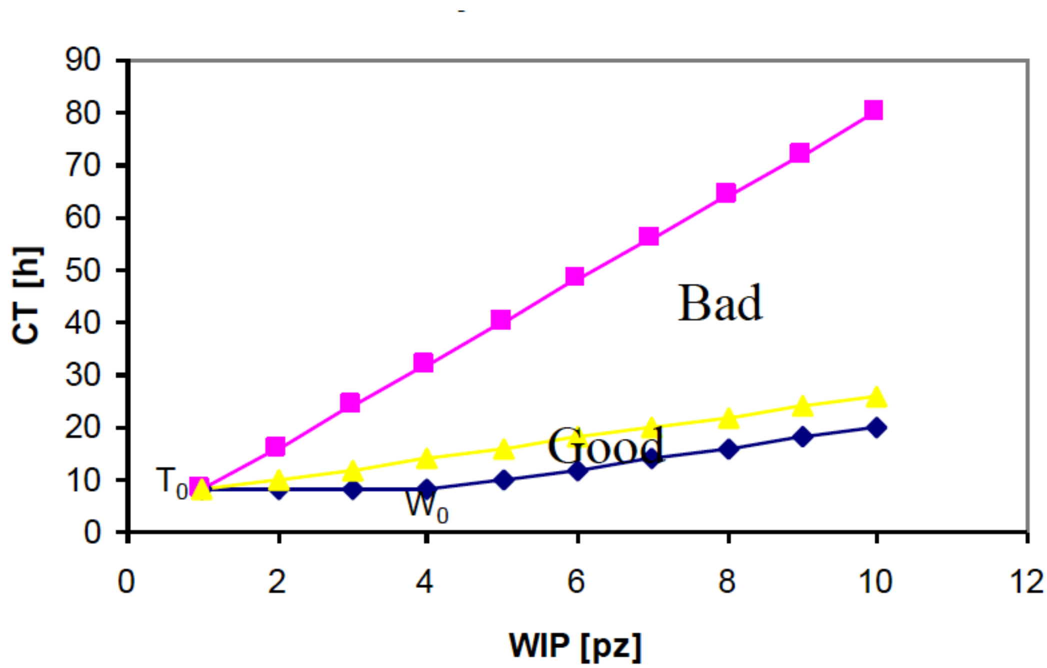


Figure 43 CT in function of WIP in the 3 cases

As it results clear, the practical worst case works as a divider for the area contained between the worst and the best case, splitting it into two subareas whose results represent "good" or "bad" performances. The result of the analysis of a given line should always fall in the "good" area, thus proving the goodness of the designed layout.

3.4 Variability parameters

The aim of this paragraph is to introduce variability and randomness at the level of the workstation analysis.

To analyze the variability is a fundamental aspect during the dimensioning phase of a production system. In fact, during the cited phase, designers have to take decisions regarding the size of the workstation, being either a real assembly or productive system station or the number of desks of the post office, in order to satisfy the demand and sustain possible demand increase. On the other hand, the risk of oversizing is always back to the corner, and would lead to a waste of resources and money.

The variability can be directly correlated to a number of aspects: first, the non-uniformity of a class of entities; secondly, the deviation from the regularity and predictability of the system behavior.

Variability can either have a **deterministic or stochastic** nature. The magnitude of a stochastic variable is statistically measured by the mean μ, while its variability by the variance σ^2 and the standard deviation σ. However, the classification of the variability of a stochastic variable relies on coefficients without dimensions like the **coefficient of variation c** or the **squared coefficient of variation c^2**. They are defined as:

$$c = \frac{\sigma}{\mu} \quad and \quad c^2 = \frac{\sigma^2}{\mu^2}$$

Basically: the ratio between the standard deviation and the mean value the first, and the ratio between their squared values the second one.

In order to compare stochastic variables any system is classified according to its variability, expressed thanks to their coefficient of variation:

- Low variability $c < 0,75$
- Moderate variability $0,75 \leq c < 1,33$
- High variability $c \geq 1,33$

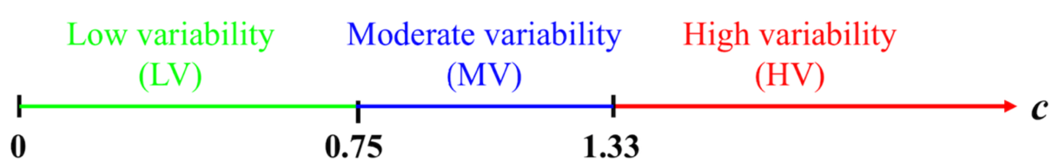


Figure 44 Variability axis slots

Recalling the part related to the internal benchmarking approach, it is possible to assign to these categories of variability one of the lines or areas depicted in the final comparative plot. In particular:

- Low variability (LV): from the Best Case to Practical Worst Case
- Medium variability (MV): Practical Worst Case
- High variability (HV): from Practical Worst Case to Worst Case.

3.5 Workstation variability

The process variability of a single workstation negatively affects performances increasing the cycle time, increasing the work in process and reducing the utilization of the workstation capacity.

Many sources of variability are present in the real world, the four main ones being **natural variability, preemptive outages, non-preemptive outages** and **reworking**.

Natural variability

The natural variability is defined as the variability not explicitly correlated to a source. Usually, it is related to workers but it can also be related to other sources such as material variations, product changes or product quality.

The natural variability of the process time is generally a LV type:

$$c_0 = \frac{\sigma_0}{t_0} < 0{,}75\ (LV)$$

Preemptive outages

This terms represent failures that could occur at any time, like tool break and consumable stockout, and interrupt the manufacturing of the job.

Thanks to the definitions of some parameters like:

$m_f = mean\ time\ to\ failure\ (MTTF)$

$c_f = coefficient\ of\ variability\ of\ failure\ times$

$m_r = mean\ time\ to\ repair\ (MTTR)$

$c_r = coefficient\ of\ variability\ of\ repair\ times$

It is possible to define the **availability** parameter and the mean value of the **effective process time**

$$A = \frac{m_f}{m_f + m_r} \qquad and \qquad t_e = \frac{t_0}{A}$$

Then, the variance of the effective process time σ_e^2 and its squared coefficient of variation c_e^2:

$$\sigma_e^2 = \left(\frac{\sigma_0}{A}\right)^2 + \frac{(m_r^2 + \sigma_r^2)(1 - A) * t_0}{A * m_r}$$

Where the first addendum represents the natural variability and the second the variability associated to the repair time.

$$c_e^2 = \frac{\sigma_e^2}{t_e^2} = c_0^2 + A(1 - A)\frac{m_r}{t_0} + c_r^2 A(1 - A)\frac{m_r}{t_0}$$

Where the first addendum again represents the natural variability, the second the variability associated to the repair time and the last one the variability associated to the variability of the repair time.

Non-preemptive outages

In this category fall all the setups or tool changes allowing for the completion of the job. The parameters to be introduced are:

$N_s = mean\ number\ of\ parts\ manufactured\ between\ two\ setups$

$t_s = mean\ setup\ time$

$c_s = coefficient\ of\ variation\ of\ setup\ time$

Assuming the probability of a setup after the manufacturing of a part to be always the same, it is possible to state setups increase the effective process time of any job according to a quantity $\frac{t_s}{N_s}$ thus providing a mean value for the effective process time equal to:

$$t_e = t_0 + \frac{t_s}{N_s}$$

The variance of the effective process σ_e^2 time is given by:

$$\sigma_e^2 = \sigma_0^2 + \frac{\sigma_s^2}{N_s} + \frac{(N_s - 1)}{N_s^2} t_s^2$$

Where the first term represent again the natural variability, the second the variability of setup time and the last one the interaction of different setups.

The squared coefficient of variation is simply found as in the previous case, this time substituting the formula for the effective variance.

Reworking for quality

A reworking increases the effective process time, reducing the utilization of the workstation and increasing the variability and the congestion of the system.

Suppose to take p as the probability to have a defective part. The control of parts quality is aimed at detecting the non-conformity and ask for a reworking when necessary, this process continuing until the non-conformity is removed from the part.

At the end, the mean value of the effective process time is:

$$t_e = \frac{t_0}{1-p}$$

The effective process time variance σ_e^2 and the squared coefficient of variation c_e^2 are given by:

$$\sigma_e^2 = \frac{\sigma_0^2}{1-p} + \frac{p * t_0^2}{(1-p)^2}$$

$$c_e^2 = \frac{\sigma_e^2}{t_e^2} = c_0^2 + p(1-c_0^2)$$

Moreover, it is possible to introduce the effective utilization of the workstation:

$$u = r_a t_e = \frac{r_a t_0}{1-p}$$

Please note a single workstation can suffer one or more of the previous sources of variability. In this case, more evaluation steps are necessary and the output data of the first evaluation are used as input for the next one. After the required number of steps, the resulting outcoming variability of the station n is used as the incoming variability of the next workstation n+1. This aspect introduce the concept of **flow variability**.

3.6 Flow variability

Having understood that the variability of the workstation n can affect the behavior of the following workstation, it is easy to note that from a wider point of view this process generates the so-called flow variability, a kind of chain reaction triggered by the workstation n that reverts on the flow as a whole.

The flow variability negatively affects performances, perturbing arrivals on the following workstations, affecting both CT and WIP and reducing the utilization of the whole line.

To deeply understand the this section it is necessary to think to look the line from a more external point of view, with respect to what done before. In fact, the aim of this analysis is not to analyze what happens inside a workstation, but to understand the interaction between workstations and the behavior of the entire line.

The useful parameters to be looked at are:

$$r_a = \frac{1}{t_a}\ arrival\ time$$

$$t_a = interarrival\ time$$

$$\sigma_a = standard\ deviation\ of\ interarrival\ time$$

$$c_a = coefficient\ of\ variation\ of\ interarrival\ time$$

Departure parameters are defined analogously:

$$r_d = \frac{1}{t_d}\ departure\ time$$

$$t_d = interdeparture\ time$$

$$\sigma_d = standard\ deviation\ of\ interdeparture\ time$$

$$c_d = coefficient\ of\ variation\ of\ interdeparture\ time$$

The in-workstation effective parameters are the result of the analysis of the previous chapter. Next figure helps to better understand this concept.

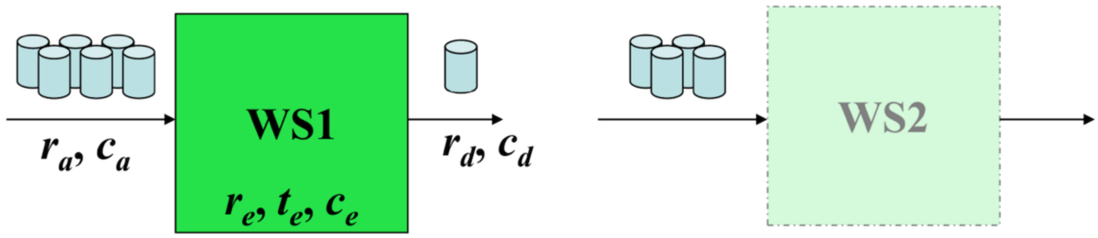


Figure 45 Interaction between workstations

Thanks to these, the average workstation utilization can be defined:

$$u = \frac{r_a t_e}{m}$$

Where m is the number of parallel machines present in a workstation.

At this point, three different cases can be analyzed, depending on the value of the workstation utilization:

- $u \approx 1$: the workstation is always busy and the interdeparture time depends on the process time, thus resulting: $c_d = c_e$
- $u \approx 0$: the workstation is almost always empty, thus the interdeparture time depends on the interarrival time: : $c_d = c_a$
- $0 < u < 1$: here considering two cases where

$$m = 1 \quad providing \qquad c_d^2 = u^2 c_e^2 + (1 - u^2) c_a^2$$

$$m \geq 1 \quad providing \quad c_d^2 = 1 + (1 - u^2)(c_a^2 - 1) + \frac{u^2}{\sqrt{m}}(c_e^2 - 1)$$

Please note the first equation is the simplification of the second one with $m = 1$.

Moving on, it is coherent to remind that in a line composed of several workstation with a constant flow without any kind of loss or rework, any parts that comes out of a workstation directly enters the following one.

When **no inventory between workstations** is present, the following holds:

$$t_a(i+1) = t_d(i)$$
$$c_a(i+1) = c_d(i)$$
$$TH = r_a$$

Eventually, final cycle time coming from the two different evaluations methodologies is the sum of the time spent in the queue and of the effective station time:

$$CT = CT_q + t_e$$

Thanks to the Little's Law it is now possible to determine the work in process.

Moreover, the **queue work in process** can be defined as: $WIP_q = CT_q * r_a$

Remind that the effective process time usually is only from 5 to 10% of the cycle time in a manufacturing system, meaning that most of the time is spent "waiting".

3.7 Queue theory

This section is treated hereafter for sake of completeness and to provide a first idea of how queue theory is used in the line analysis. In fact, **the science that analyzes "waiting" is the queue theory**.

Generally, a queue depends on many factors, some of these concerning the arrival process (single job or single batch, arrival time deterministic or stochastic), some the manufacturing process (single machine or parallel ones, process time deterministic or stochastic) and some others from its intrinsic typology (limited or unlimited queue, FCFS, …).

The parameters describing a queue system are:

$r_a = workstation\ arrival\ rate\ \left[\frac{job}{time}\right]. If\ serial\ line\ without\ loss\ r_a = TH\ in\ every\ WS$

$t_a = mean\ interarrival\ time$

$c_a = coefficient\ of\ variation\ of\ interarrival\ time$

$m = number\ of\ parallel\ machines\ in\ the\ workstation$

$B = buffer\ dimension\ (b = \max number\ of\ jobs\ in\ the\ system)$

$t_e = mean\ effective\ process\ time$

$c_e = coefficient\ of\ variation\ of\ effective\ process\ time$

Performances of a queue system are measured by:

$p_n = probability\ of\ n\ job\ in\ the\ workstation$

$CT_q = mean\ waiting\ time\ in\ the\ queue\ of\ the\ workstation$

$CT = mean\ time\ spent\ in\ the\ workstation$

$WIP = mean\ work\ in\ process\ in\ the\ workstation$

$WIP_q = mean\ work\ in\ process\ in\ the\ queue\ of\ the\ workstation$

Queue system categories are generally identified thanks to the **Kendall notation**. Kendall notation is a set of 4 letters each one having a different meaning for the given queue system:

Kendall notation : **A / B / m / b**

Where:

A = statistical description of interarrival time:

- D = deterministic distribution (exponential)
- M = exponential distribution (Markovian)
- G = general distribution (normal, uniform, …)

B = statistical description of process time:

- D = deterministic distribution (exponential)
- M = exponential distribution (Markovian)
- G = general distribution (normal, uniform, …)

m = number of machines in the workstation

b = max number of job allowed in the system.

Model M / M / 1 / ∞

This model is the easiest one and is taken as an example of the application of the studied theory. As it should be clear now, this queue system is represent by a markovian distribution of both interarrival and process times, it uses a single machine and can host an unlimited queue.

Taking as data the mean interarrival and process times and the number of job in the system (that is a memoryless system), two main hypothesis are done: first, the probability

p_n representing the probability the system is in the state number n is chosen and the jobs arrive one by one, they are manufactured one by one and such events determine the change of state from n-1 to n or from n to n-1.

By means of a simple demonstration, it is possible to understand that:

- $p_{n-1} * r_a$ is the rate the system moves from state n-1 to state n
- $p_n * r_e$ is the rate the system moves from state n to state n-1

providing the system to be stable when $p_{n-1} * r_a = p_n * r_e$.

Moreover, it is possible to determine the values of WIP, CT, CT_q and WIP_q exploiting geometrical series and derivates. The demonstration is left aside because is beyond the scope of the dissertation.

The final formulas are:

$$WIP = \frac{u}{1-u}$$

$$CT = \frac{WIP}{r_a} = \frac{u}{r_a(1-u)} = \frac{t_e}{(1-u)}$$

$$CT_q = CT - t_e = \frac{u}{(1-u)} t_e$$

$$WIP_q = r_a \frac{u}{(1-u)} t_e = \frac{u^2}{1-u}$$

Furthermore:

$$TH = r_a \quad and \quad u = \frac{r_a}{r_e} < 1 .$$

Model G / G / 1 / ∞

Following the Kendall notation it is possible to understand this model consists in a queue with general probabilistic distribution for both the interarrival and process times, while the one machine is present only. The queue size is supposed to be infinite.

Briefly, to evaluate the queue cycle time it is necessary to provide **the Kingsman equation**, also named **VUT relation**. "VUT" is an acronym standing for system variability

(V), system utilization (U) and system process time (T). In fact, the queue cycle time is evaluated as:

$$CT_q = V * U * T \cong \left(\frac{c_a^2 + c_e^2}{2}\right)\left(\frac{u}{1-u}\right) t_e$$

It is worth to note the first term of the right hand equation represents the variability V, the second the utilization and the last one the process time: the product of all the 3 components provides the unknown time.

Please note, when $c_a = c_e = 1$ the Kingsman equation provides the same queue cycle time provided for the M / M / 1 /∞ model.

Parallel machines

In case of parallel machines, thus providing a model of the type M / M / m /∞ or G / G / m /∞, the formulas of the queue cycle time suffer changes, becoming:

- **M / M / m /∞ model** :

$$CT_q = \frac{u^{\sqrt{2(m+1)}-1}}{m(1-u)} t_e$$

- **G / G / m /∞ model** :

$$CT_q = \left(\frac{c_a^2 + c_e^2}{2}\right)\left(\frac{u^{\sqrt{2(m+1)}-1}}{m(1-u)}\right) t_e$$

Furthermore,

$$TH = r_a \quad and \quad u = \frac{r_a}{r_e} < 1 \,.$$

The queue model cases M / M / 1 / b and G / G / 1 / b are not investigated but represents surely represent a further development of the queue theory.

4. Anylogic implementation

The second part of the project deals with the implementation of the plant material movements with the Anylogic software. This part is necessary to verify the goodness of the results obtained during the previous phase.

In fact, in such a way, it is possible to capture both the lines and the warehouse have been dimensioned properly to sustain a certain process variability.

Anylogic is one of the most powerful modeling software on the market. Along with FlexSim is both used in academic and working environments for many purposes.

4.1 Modeling

Modeling is a way used to solve real-world problems. Even though some constraints and approximations will always be present, it is fundamental because many times it results impossible to experiment with real objects in order to find the proper solution.

For this purpose, it is possible to create a **model**, build through a **modeling language**, to represent the real-life systems and their situations. As mentioned before, the process adopts abstraction: details thought to be important are included, while the remaining ones are left aside. Indeed, the model is always less complex than the original system.

After the model construction phase, and sometimes while doing so, it is possible to start exploring and understanding system's structure and behavior, such as to test how it will behave undergoing a set of various conditions, play and compare scenarios, and optimize the system as well. After the solution is found, it is then mapped to the real-world scenario.

Modeling is about finding the way from the problem to its solution through a risk-free world where we are allowed to make mistakes, undo things, go back in time and start over again. [5]

Many types of models are present, including mental ones that are used to understand how real-world things work and all the taken decisions are based on mental models.

On the other hand, computer are powerful modeling tools, offering users a flexible virtual environment where it is possible to recreate almost everything. Naturally, there are many of computer models, ranging from basic spreadsheets that allow anyone to model expenses to complex simulation modeling tools that help much more experienced and skilled users to explore dynamically more complex systems like battlefields or consumer markets.

Analytical and simulation modeling

In this paragraph the main differences between analytical and simulation modeling are defined to understand the relevance of the utilization of the last in this project.

Analytical models such as Microsoft Excel spreadsheets hides a quite simple technology behind them: first, it is required to enter the data inputs in some cells and later, outputs can be observed in others. Formula or scripts link the input to the output values. Add-ons allow to perform parameter variation, Monte Carlo analysis, optimization experiments.

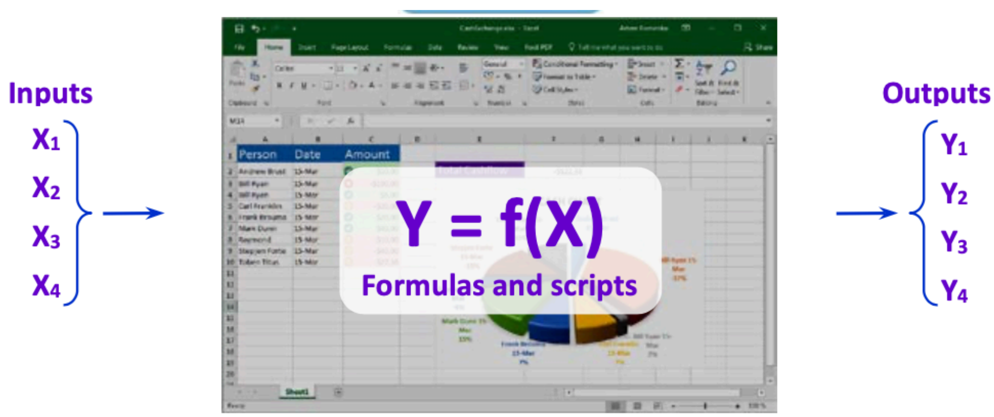


Figure 46 Analytical model parameters

Anyhow, a large class of problems where the formula-based analytic solution is either hard or impossible to find is present. This class includes dynamic systems that could present a non-linear behavior, a "memory" property or non-intuitive influences between variables, such as time and causal dependencies; all the above combined with uncertainty and a very large number of parameters.

Many times, it is not possible to find out the right formulas or to build a mental model for such a system. Just consider the example of the modeling of the behaviors of passengers inside a rail station during rush hours: using Excel spreadsheets results impossible to manage factors such as travel schedules or the interaction between passengers.

Formulas that are good at expressing static dependencies between variables typically do not do well in describing systems with dynamic behavior. It is why another modeling technology – **simulation modeling** – is used to analyze dynamic systems. [5]

A so-called "simulation model" is an executable model. To run it, creates a trajectory of the system's state changes. The outputs of the model are produced and can be taken under observation while the model is running. This modeling requires specific software tools, each of them using specific simulation languages. At the end, the model will offer a high-quality analysis of a dynamic system.

Many people, especially those with programming or particular Excel skills, try to exploit spreadsheets to model a dynamic-type system.

Unluckily, problems arise while trying to capture more and more details, overwhelming the model structure that will result in a too slow or unmanageable environment, later thrown away. It is now clear it is impossible to capture all the details through an analytical model, and that is the reason why simulation models are used.

Simulation modelling pros

Hereafter, **six of the major advantages of simulation modelling** are reported. Mainly, simulation modelling:

- Allows the system analysis and to find solutions where methods like analytic calculations and linear programming fail
- Once chosen the abstraction level, it results easier to develop a simulation model rather than an analytical one: it typically requires less thought, and its development is incremental, scalable and modular
- The structure of a simulation model reflects the system one
- In a simulation model, it is possible measure values and track entities within the supposed level of abstraction. Moreover, measurements and statistical analysis can be added at any time

- One of the great advantages is the ability to play and simulate the system behavior in time. Animations are useful for demonstrations, verification and debugging
- Simulation models are way more convincing than Microsoft Excel spreadsheets. Using a simulation model rather than spreadsheets helps designers to gain advantage over those only using calculations.

Simulation modelling applications

Nowadays, simulation modeling has accumulated a wide number of success stories in a large and diverse range of applications area. Being a new modelling method, it is worth to expect simulation modelling to enter an ever-larger number of areas thanks to the growing of computers power and technologies.

Just to provide an example, the figure below describes some of the possible application areas of this type of modeling, each one approximately sorted by its corresponding abstraction level.

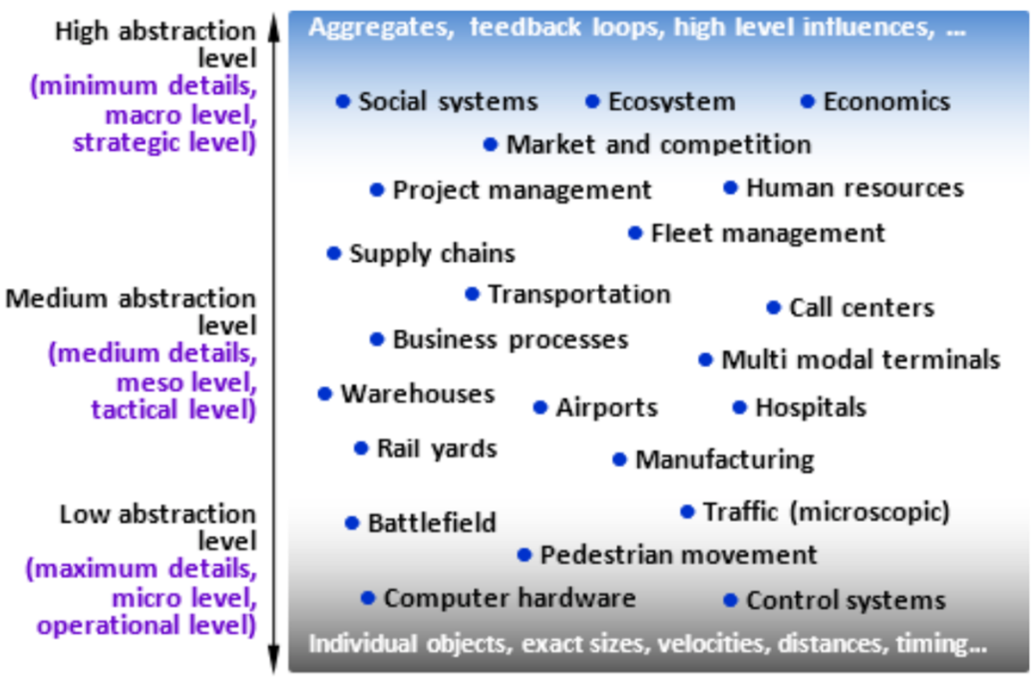


Figure 47 Levels of abstraction

With a deeper insight of the picture, it is evident that at the bottom physical-level models used for highly detailed representations of the real-world objects are present. At this level of abstraction, it is worth to highlight and take care about physical interaction, velocities, dimensions, timings and distance.

On the other hand, the models at the are highly abstract and usually use aggregates like consumer populations and employment statistics rather than individual objects are reported at the top. These last ones can help the user to understand relationships without requiring intermediate steps modeling.

Of course, intermediate abstraction levels models are present. Just imagine to model the emergency department of an hospital: it should be worth to take care about physical space if it is necessary to know the time needed to for someone to walk from emergency room to an x-ray station, but the physical interaction among personnel and people in the building results irrelevant if the building is supposed to be uncongested.

Thus, it is clear that **choosing the right abstraction level** is critical to the modeling project's success and it results reasonably easy once it has been decided what to include in the simulation such as what will remain below the level of abstraction.

Anyhow, it is normal, sometimes desirable, to occasionally reconsider the model's abstraction level in the model development process. Many times, details are added if and when needed by starting from a higher abstraction level.

Three methods of simulation modeling

A method is defined as a framework we use to map a real-world system to its model. Just think of a method as a type of language or a sort of "terms and conditions" for model building. [5]

Basically, modern methods of simulation modeling are **three: discrete event, agent based** and **system dynamics**.

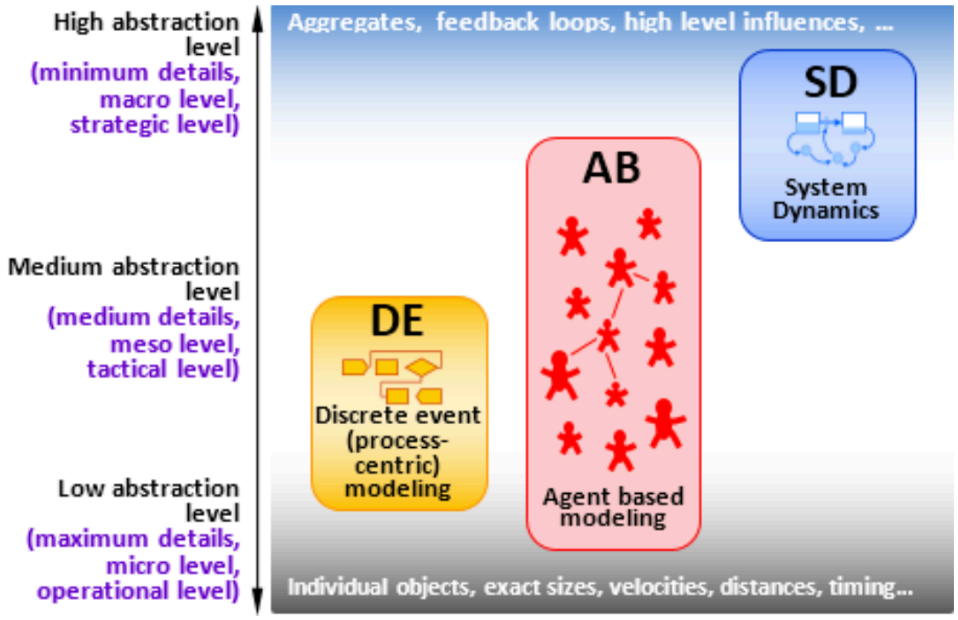


Figure 48 Model type in function of the level of abstraction

As it results clear from the picture, system dynamics modeling assumes a high abstraction level, while discrete event modeling a medium or medium-low one. Instead, agent-based modeling can vary from very detailed models to highly abstract ones.

Please remind the choice about the method has to be done once carefully considered the kind of system to be modeled and modeling goals. Sometimes, the best way to model the various parts of a system is to use different methods. In such a way, a multi-method model is implemented.

4.2 The plant analysis

Once introduced the software, it is now important to underline the reason why it has been implemented in this project. From a general point of view, Anylogic is used to speed up a first validation phase for the plant design. Indeed, the plant has been dimensioned in its parts basing on average assembly times provided by the INSIA institute taking into account several constraints.

With the last ones, many assumptions related to both the assembly lines and the warehouse dimensioning have been taken.

With the steps and the work explained in the following a first validation of the design can be reached. First, simulation models of lines and warehouse are built starting from the data of the dimensioning phase. Later, simulations are run and congestion are detected if present. The goal is to understand whether such **dimensioning is worth to sustain a certain line variability or corrective actions should be taken** because of the appearance of congestion stations.

This phase is divided into **lines validation** and **line and warehouses optimization**.

Lines validations

The first and most important analysis is the one done for the lines. In fact, while it is quite simple to change the warehouse layout, it would be much more time demanding and expensive to change the configuration of the two assembly lines.

As discussed above, the idea is to run simulations to understand whether congestions occur or not. From the physical point of view, a **congestion is represented by the fact that no more than one car bodies structure can wait in between two stations** because no space would be left for the movement of the operator. If this happens, the previous station should wait more to start work and time is lost. Of course, it has to be avoided in whatever way.

The starting point for the analysis is the **line routing** and the **workstation assembly standard times**, both determined in the dimensioning phase based on average times for each operation. Hereafter, the table with routing and standard times is reported again for clearness:

	TIME [min]		
Name of the modules in the different stations	Min	Max	Avg
Main hoop and HV voltage wiring	35	37	36
LV wiring and brake line	30	45	37,5
Traction and transmission without electronics	30	45	37,5
Electronics and first cooling system part	30	40	35
End cooling system, and pedal box	35	45	40
Steering , seat, safety harness	32	48	40
Nose + Front suspension part 1	32	48	40
Front suspension part 2	30	45	37,5
Rear suspension part 1	30	45	37,5
Rear suspension part 2	30	45	37,5
Front wing, diffusor, wheels and rear and lateral wings + quality check at the end of the line [15 min]	34	42	38

As already discussed, 11 stations are present per line and the reported times values are representing the best and worst case such as the average time for station. Here, the **best case** is defined as the sum of the minimum times of each operation performed in the given station.

On the contrary, the **worst case** is defined as the sum of the maximum times required for the same ones. Ideally, the best case is representing a very high line efficiency, while the worst one a kind of unstable and not optimized sequence of operations. During the dimensioning phase, the lines have been set to their average value because the aim was to both avoid a too conservative and a completely constrained layout. In fact, in the first case useless expenses would be sustained while in the second one, corrective actions, much more onerous than design ones, should have been taken. Basically, the idea is to optimize in order to save costs.

Thus, as mentioned before, the single line is simulated in the Anylogic environment by means of **Space Markup** palette tools before and of **Process Modeling library** later.

Please note again these two libraries are the ones used to validate the lines only in terms of line balancing, avoiding bottlenecks. For this reason, all what is dealing with the loading and unloading of materials at the two extremities of the line such as the physical material movement on the conveyor, exploiting the **Material Handling library** tolls, will be assessed in the following paragraphs.

Space Markup tools are used to create a network. A **network** is made of nodes and paths. A **node** is a place where agents may reside or perform a given operation while a path is route that can be exploited by agents to move between nodes. **Agents** are model building blocks that can be used to model operations of the real world.

Once the network representing the line is created it can be cut and paste for the following simulations because the structure of the lines is always the same. Henceforth, the scheme reported is used from and now but displayed only once.

Figure 49 Network representation in Anylogic environment

Later, Process Modeling library tools are used to simulate the line assembly works. Mainly, standard times are used in different forms. The starting point is to provide to each of the station a deterministic time equal to the average of each assembly stations. De facto, this only represent a second validation of the lines dimensioning because they have been build starting exactly from these data. The four blocks used are the following:

Source: a source block generates agents. This is normally used as a process flowchart starting point and in the following simulations represents the first station. Again, please note this convention is taken because here the line balancing is analyzed only. On the other hand, the source block could not have been used to represent the first assembly station.

Conveyor: this block simulates a conveyor, which is moving agents along a defined path at a given speed. Moreover, it preserves a minimum distance between them. A conveyor can either be an accumulating conveyor or a not accumulating one.

The firsts, do not stop when agents cannot exit at the exit points, and would continue moving remaining agents until the maximum number is reached and the conveyor is fully filled.

The second, would stop if the first agent cannot move further. This block has been used to simulate the bi-rail conveyor used to move car bodies along the line.

The conveyor is able to **sustain no more than one workpiece** per time, thus representing the **congestion parameter** that could crash the simulation. The speed of the conveyor is considered 10 m/min.

Delay. This block delays agents for a given amount of time, dynamically evaluated. The time can be stochastic and may depend on the agent as well as on any other conditions. In the project simulations, this block has been exploited to represent the processing time of assembly stations.

Sink. This last block disposes incoming agents and is usually used as a final point for a process flowchart, because it completely removes the agents from the model.

Each of the previous mentioned blocks, during simulations shows three numbers: the one on the left sides represent the entered agents, the one on the right the exit ones, and the one on the top the number of agents present in the block at the simulation time. An example is reported in the following.

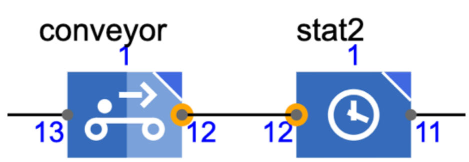


Figure 50 Conveyor and Delay blocks during simulation running

At the end, the representation of the whole line by means of logical blocks figures like it follows:

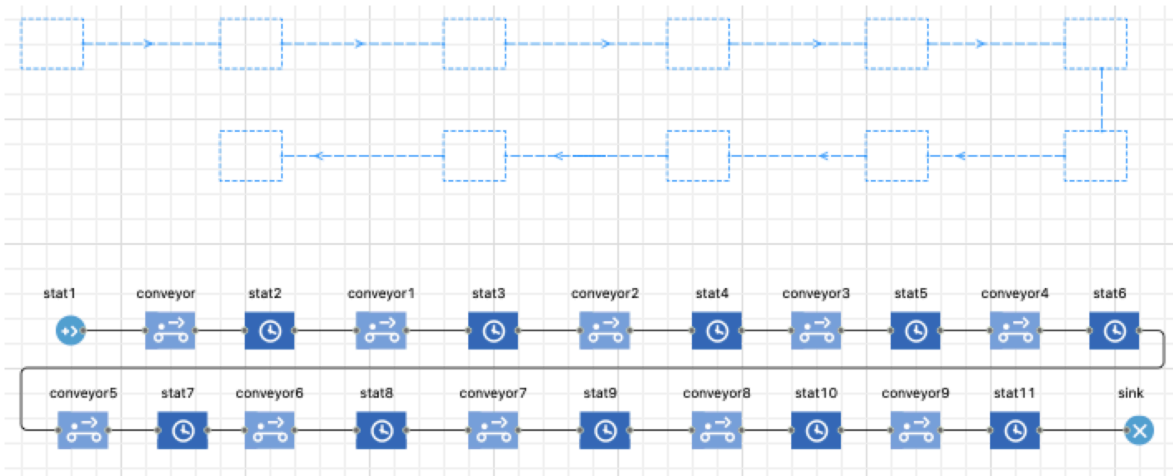


Figure 51 Entire line representation in Anylogic environment

After that, each block is selected to host the proper parameter values: source block receives inter arrival time as the first assembly station, delay blocks host the average production time in this first attempt and paths are assigned to their related conveyor blocks, defining length of the conveyor and speed of movement too.

The simulation is run and, as known, no congestions arise.

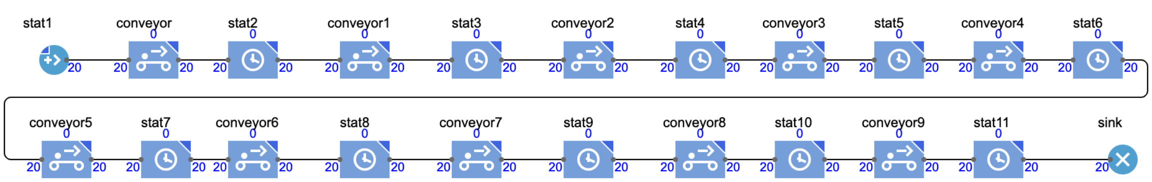


Figure 52 Simulation with deterministic times

Introducing line variability

As already mentioned in the previous, the successive step is the introduction of **line variability**. In this project, this problem has been addressed substituting to workstation deterministic standard times a value that is the result of a chosen statistical distribution. The effects of this operations can be easily noticed running the model, that could create congestion in the line or not.

The statistical distribution chosen for this aim are the following:

Triangular distribution: this is a continuous distribution bounded on both sides; often used when no or little data is available, but rarely portrays an accurate representation of a data set. The triangular distribution can take on very skewed forms including negative ones. For the case where mode is either the minimum or the maximum value, it becomes a right triangle. The parameters of this distribution are:

min	The minimum x-value
max	The maximum x-value
mode	The most likely x-value

For project purposes, the minimum value is represented by the previous defined best case, the maximum by the worst one and the mode by the average time. Just to clarify, the graphical representation of the triangular time distribution of the first assembly station is reported hereafter: min value 35, max 37, mode 36.

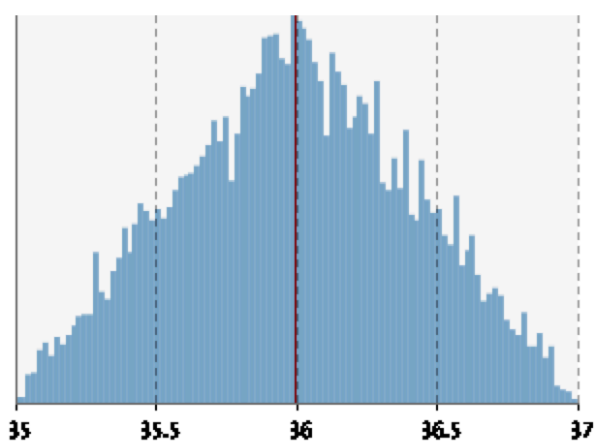


Figure 53 Example of Normal distribution

By running the simulation, it is clear the line can sustain this type of variability because the simulation brings to an end all the pieces required for the weekly production. Next picture shows it in a clearer way.

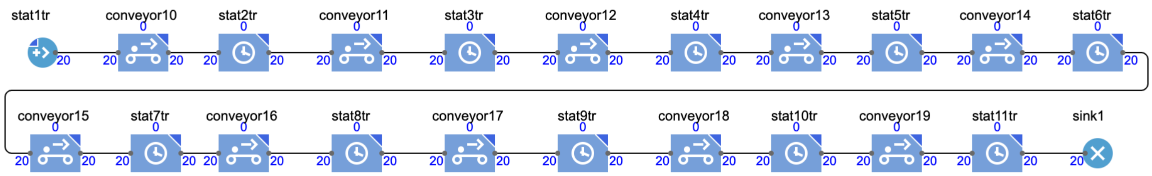


Figure 54 Simulation with triangular distribution

Normal distribution. It is an unbounded continuous distribution, sometimes called a Gaussian distribution or bell curve. The normal distribution finds many applications in statistics because of its property of representing an increasing sum of small, independent errors.

Usually, it is used as approximation of the Binomial distribution when the values of n, p are appropriate. It is used to represent symmetrical data, but suffers from being unbounded on each side.

The parameter representing the normal distribution are:

sigma or shape parameter	Standard deviation
mean or shift parameter	Mean value

The standard deviation is a measure of the amount of variation of dispersion of a set of value. In fact, a low standard deviation represents values tend to be close to the mean while on the opposite a large standard deviation indicates values are much more spread out over a wide range. For a finite sample of N observations, the standard deviation is defined by le letter s ad follows:

$$s = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N - 1}}$$

Where x_i is the observed values of a sample item and $\bar{x}$ is the mean value of the total observations.

Moreover, the mean value of a sample is defined as: $\bar{x} = \frac{\sum x_i}{n}$ where x_i are measured x values, and n represents the number of items in the sample.

Now, considering the normal distribution as a continuous function, thus not coming from sampling methodologies, it possible to say it has both probability density function (PDF) and cumulative density function (CDF), that could be shown parameterized by its mean (μ) and its standard deviation (σ):

$$PDF = f_N(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-\mu)^2}{2\sigma^2}}$$

$$CDF = F_N(x) = \int_{-\infty}^{x} f_N(t)dt$$

Given the not-nice closed form of the CFD, hereafter it will only be represented using its definition in terms of the PDF. Just to have an idea of how the shape can change changing the different parameters, PDF and CDF representations are displayed in the following picture.

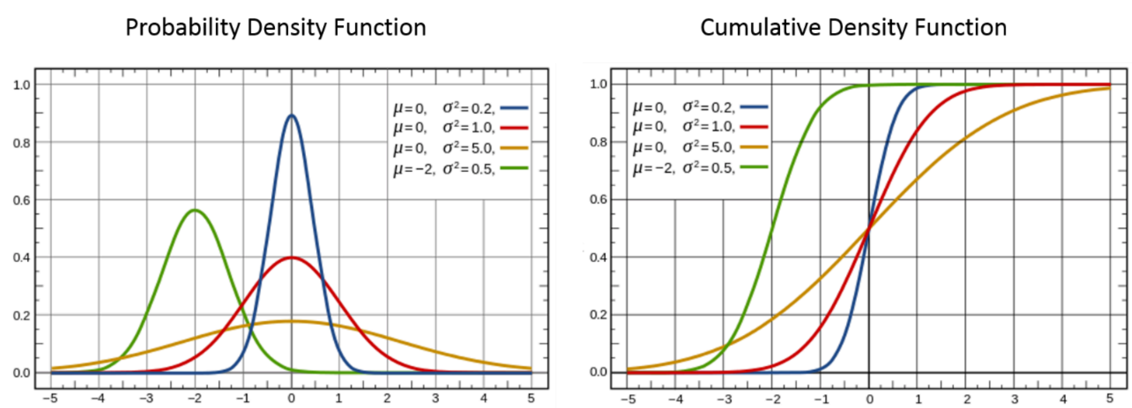


Figure 55 PDF and CDF for Normal distribution

In the literature, different ways to exploit this distribution are present. First and most important, by means of the Table for the standard normal distribution, a normal distribution with mean value μ=0 and standard deviation σ=1, allowing the user to perform calculations for any normal distribution.

In fact, the following formula can be used in two ways: first, a **direct approach** where the percentage of population's elements with a value of the investigated characteristics greater (or lower) than a set limit z_{lim} is found; secondly, the **inverse**

approach, used to determinate the limit value z_{lim} which leaves on its right (or left) a set percentage of population's elements.

The formula is: $z = \frac{x-\bar{x}}{\sigma}$ where z is measured in "units of standard deviations".

For project purposes the **inverse approach** is used as follows: basically, for each station, the standard deviation has been evaluated exploiting the mentioned formula. This result is different station to station because it has been supposed to want to cover a defined percentage of time values within the minimum and the maximum one, thus having the value of z yet and defining the one for the standard deviation thanks to the cumulative distribution formula. The used formula is the following one:

$$\sigma = \frac{x - \bar{x}}{z}$$

Basically, given the symmetry of the distribution, the maximum (or minimum) value has been taken as the related x value; the average value remains the mean and the z values are taken by the table for two different situations, respectively:

- 95% of the times fall inside the min and max value (thus z = 1,96)
- 99% of the times fall inside the min and max value (thus z = 2,576).

In this way, the resulting distribution standard deviations are:

	TIME [min]			SIGMA for 95%	SIGMA for 99%
Name of the module	Min	Max	Avg		
Monocoque and HV voltage wiring	35	37	36	0,510	0,388
LV wiring and brake line	30	45	37,5	3,827	2,911
Traction and transmission without electronics	30	45	37,5	3,827	2,911
Electronics and first cooling system part	30	40	35	2,551	1,941
End cooling system + pedal box	35	45	40	2,551	1,941
Steering , seat, safety	32	48	40	4,082	3,106
Nose + Fron suspension 1	32	48	40	4,082	3,106
Front suspension 2	30	45	37,5	3,827	2,911
Rear suspension 1	30	45	37,5	3,827	2,911
Rear suspension 2	30	45	37,5	3,827	2,911
Front wing, diffusor, wheels and rear and latera	34	42	38	2,041	1,553

Just to figure out the final shape of one of the distributions, the first assembly station is taken as an example with the related σ value for the 99% of the cases. As it is clear, the shape is very tight with a standard deviation σ = 0,51 and a mean value $\bar{x}$ of 36 minutes.

Once explicated the way data are used, simulations are run: also, in these two cases the line perfectly fits the production and its intrinsic variability without congestion. To prove it, screenshoots of the run simulations are reported.

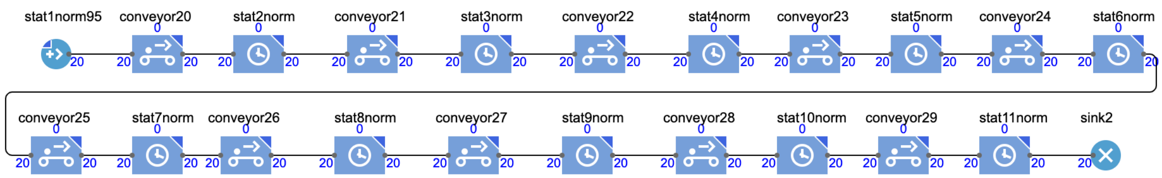


Figure 56 Simulation with normal distribution and cumulative probability equal to 95%

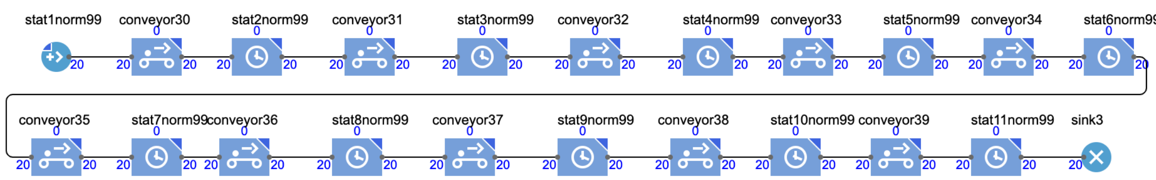


Figure 57 Simulation with normal distribution and cumulative probability equal to 99%

Uniform distribution. The uniform distribution is a continuous distribution bounded on both sides in an interval between a minimum and a maximum value. Its probability density does not depend on the value of x, and it is a special case of the Beta distribution. Frequently, it is called "rectangular distribution".

This distribution is used for the representation of random variables with constant likelihood in any interval between the minimum and the maximum value. The probability of the max value is zero, meaning that it never occurs.

Thus, the two simple parameters of the uniform distribution are:

min	The minimum x value
max	The maximum x value

This last distribution is considered for project purposes as a kind of pessimistic analysis. In fact, as already cited, the average value represents the most likely value in the reality. By doing so, the same probability is given to each of the values inside the minimum to maximum value interval, something way higher than the real situation.

The first station uniform probabilistic distribution, between minimum value 35 and maximum 37, is reported here down as an example:

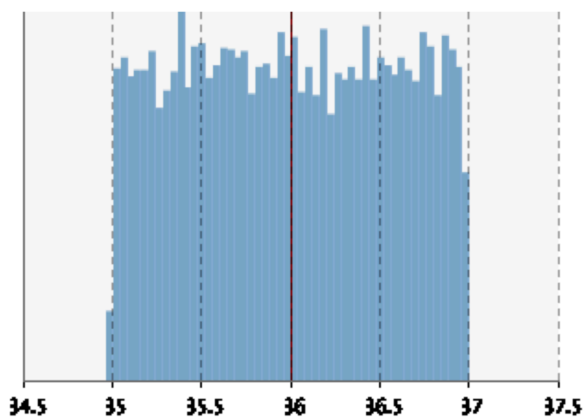


Figure 58 Uniform distribution example

Once more, the run model does not show any arisen congestion. Picture are proving it here after.

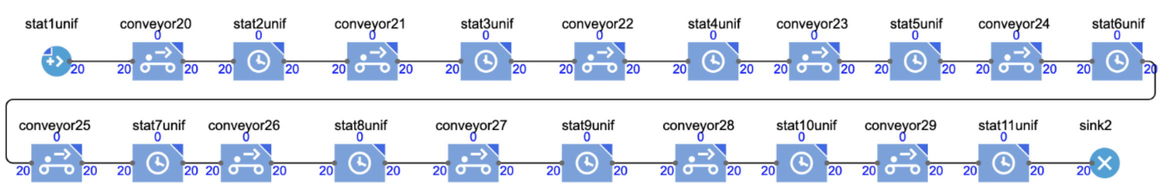


Figure 59 Simulation for uniform distribution model

Exponential distribution. This next case is a continuous distribution bounded on its lower side. The shape is always the same, and it starts from a lower bound finite value continuously decreasing at increasing x values. The exponential distribution decreases swiftly for increasing x.

Historically, this distribution is used to portray the time between random occurrences, such as the time between arrivals at a given location in a kind of queueing model or the time between failures in reliability ones. Furthermore, it serves as a representation of the services times of specific operations.

The exponential distribution receives as inputs two parameters:

beta	The shape parameter
min	The minimum x value

For this project, taking into account the reduced number of data, it has been chosen to exploit this distribution in the following manner: the created exponential distribution takes the previous called average value as the value dividing the cumulative probability into equal parts of 50% each.

Of course, the distribution is not symmetrical thus this value does not represent the average value of the exponential distribution. De facto, knowing that the probability density function expression is

$$F(x,\beta) = \beta e^{-\beta x}$$

while the cumulative probability expression is the following one

$$P(x,\beta) = 1 - e^{-\beta x}$$

it is possible to determine the value of β with the inverse equation

$$\beta = -\frac{\log(P)}{\log(e) * x}$$

where the P value is equal to 50% and the x value is considered the average of the previously available data. In such a way a distribution with min value equal to the "best case" and β obtained from the mentioned equation is attained.

Please note, this is the only way the distribution can be modeled with the available data and can be seen with the meaning of well-trained operators on average working at a faster speed with respect to the one of (ie.) the normal distribution, while few workmen take longer to perform their tasks. In the next table, values of β and μ (average value of the exponential distribution) are obtained for all the standard times.

It is worth to note this solution provides asymptotic values outsides our starting interval. Unluckily, this is the drawback of the limited modeling tool that has been exploited. Indeed, time values outside of the interval can be experienced with very low probability. Last but not the least, the μ average value is obtained by means of the exponential distribution characteristic saying that

$$\mu = \frac{1}{\beta}$$

Please note same value of β are highlighted with the same color meaning the same distribution is used for the related stations.

	TIME [min]				
Name of the module	Min	Max	Avg	BETA	exp distrib avg value
Monocoque and HV voltage wiring	35	37	36	0,69	36,44
LV wiring and brake line	30	45	37,5	0,09	40,82
Traction and transmission without electronics	30	45	37,5	0,09	40,82
Electronics and first cooling system part	30	40	35	0,14	37,21
End cooling system + pedal box	35	45	40	0,14	42,21
Steering , seat, safety	32	48	40	0,09	43,54
Nose + Fron suspension 1	32	48	40	0,09	43,54
Front suspension 2	30	45	37,5	0,09	40,82
Rear suspension 1	30	45	37,5	0,09	40,82
Rear suspension 2	30	45	37,5	0,09	40,82
Front wing, diffusor, wheels and rear and lateral	34	42	38	0,17	39,77

Just to provide an idea of the shape of the distribution the first raw is taken as an example and simulated thanks to the Anylogic tool. For it, a minimum value of 35 and a β parameter of 0,69 are considered. The resulting distribution is the next one.

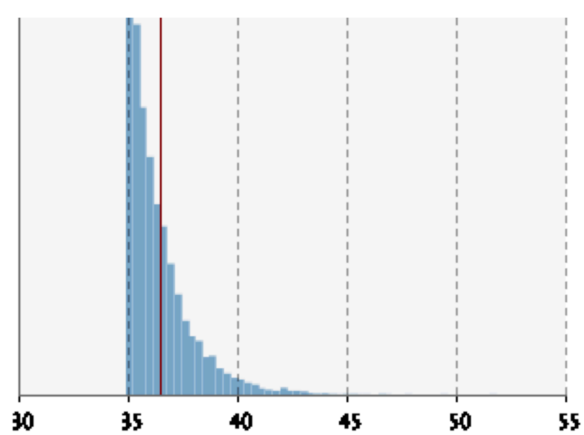


Figure 60 Exponential distribution example

Here, for the first time in the simulations, an error occurred. Please remind the error is dealing with the accumulated car bodies on each conveyor. In fact, a maximum number of 3 car bodies is reached. Of course, this is not possible because of physical constraints, meaning the n workstation waiting for the n+1 to release the line buffer to come back working.

At the end, the production is completed with a consistent delay.

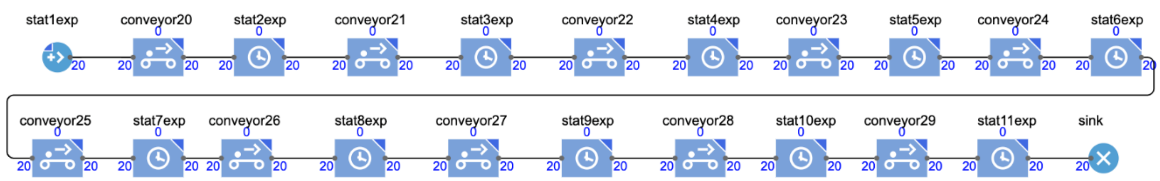


Figure 61 Exponential distribution run simulation

The following table resumes the main parameter for the run models.

DISTRIBUTION	RUN without delays [Y/N]	Time 1 unit out [min]	Time 20 units out [min]
Deterministic	Y	390	1150
Triangular	Y	387	1169
Normal 95%	Y	378	1187
Normal 99%	Y	386	1168
Uniform	Y	375	1190
Exponential	N	426	1420

Eventually, only the exponential distribution shows problems with the designed lines, resulting in a final delay of 36 minutes with respect to the deterministic times the line has been dimensioned on.

Line and Warehouse operations optimization introduction

In the next chapters the problem of **line and warehouse optimization** is addressed by means of **Material Handling library tools** too. The task here, is to avoid material handling overwhelming and to graphically provide a 2D and 3D representation of both the line assembly stations material movement and general warehouse loading and unloading operation, meaning:

- Trucks unloading at the receiving dock and raw material stacks and racks loading
- Raw material transportation to the first assembly station and its loading on the conveyor
- Line assembly stations movement and relative buffers, when present
- Line conveyor unloading at the last station and final product stacks loading
- Stacks unloading and shipping container loading at the shipping dock.

Of course, for the above-mentioned simulations some approximation have been taken either for the luck of the chosen material handling tools representation in Anylogic or for the complicated plant geometry. In fact, **only one line is represented** with the mentioned software.

De facto, this does not represent a real problem because the two lines are identical and it is assumed assumptions and approximations made for the first line hold for the second one too. Moreover, the container unloading operation is simulated for car bodies only. This last choice is done because of the meaning of this module.

In fact, by analyzing the moving behavior of the bulkier component of the assembly, it is possible to graphically understand whether problems arise or not inside each assembly stations.

Please note the spare parts movement, meaning transportation of product codes pallet from the receiving warehouse to a particular assembly station, is something that is performed by means of other resources not simulated in the following but taken into account in the plant design face of chapter 2.

Moreover, remind that these tasks are accomplished before the start of the production thus they do not imply further material handling tools utilization during working hours.

At the end, the weekly production of one line only, thus 20 units, is simulated as a representation of the whole process by means of the previously cited Process Modeling and new Material Handling libraries blocks, each of one explained in the following. It is worth to note this work has been done in the Anylogic free environment first, and later implemented on the real plant layout.

Line optimization

Line optimization represents the longest and more demanding phase of the simulations. Here, none of the previously used Process Modeling library blocks is exploited again. On the other hand, the next blocks are used:

Queue. This Process Modeling block represents a buffer (or queue) of agents that are waiting to be accepted by the next flowchart block. Its capacity can be dynamically changed, while the discipline can be chosen as FIFO (first in - first out, the default one), LIFO (last in – first out) or priority-based. When the queue is full, the last incoming agents can cause the one of the others to be thrown out of the queue the outPreempted port.

Optionally, a maximum waiting time can be associated with an agent; In this last case it would be thrown out by means of the outTimeout port it time is elapsed. For project purposes, it has been exploited to simulate a sort of line buffer before the first assembly station. As it is visible from the Autocad drawing this is not physically present, but it results necessary for the simulation because is associated with a node, the picking location to load the conveyor.

Next blocks all belong to the Material Handling library.

Convey. The convey block transports incoming agents, like material items, by means of conveyors to a specified destination point. It is the only block controlling items movement within a conveyor network. The to-be-followed route can be calculated automatically or specified explicitly by the user as a sequence of conveyors.

In the automatic evaluation case, the user can decide whether to include or dismiss certain routes. Here, the conveyor block is the Space Markup tool used that is associated to the Convey block. Moreover, a continuous movement can be simulated assembling more conveyors one to the other, later represented by a sequence of convey blocks.

Other Space Markup elements useful for the Convey block implementation are the so called “Position on Conveyor” and “Station”. The first simply represents a fixed position on the conveyor path that is chosen as a possible waiting point for the material item, while the second, associated with an intrinsic delay time, represent a manufacturing or assembly station whit a defined capacity. By setting the two parameters for the Station, each of the assembly station is represented with its deterministic or probabilistic time.

For the project, the deterministic one only is simulated because assembly line validation has been completely addressed yet.

Furthermore, convey blocks are used to simulate the entire on-conveyor movement of the car bodies. Dimensions are set as the real ones. Unluckily, it is not possible to represent an overhead conveyor with these tools. Indeed, a simple roller one is graphically represented. Further approximations are explained later.

Move By Crane. This block performs the movement of agents, like material items, by means of a crane. The transportation of the block can be either described in terms of speed, set by the corresponding space markup element parameter, or in terms of time the crane takes to transport the agent. This block can select transportation agents according to a default pattern chosen by the software or a custom one specified by the user.

As mentioned before, a Move-by Crane block requires a “Jib Crane” Space Markup element associated. There, all the speed and time parameters can be easily defined.

For project purpose, this block is used as a conveyor loading and unloading tool exploited at the first and last station respectively. Speed parameters are set to avoid car bodies accumulation both in the beginning of line buffer and at the end of line unloading station.

Please note in the drawing the conveyor is of the continuous type, and does not report any jib crane. Thus, this is the assumed approximation.

At the end, the graphical and logical block representation looks like in the following screenshot.

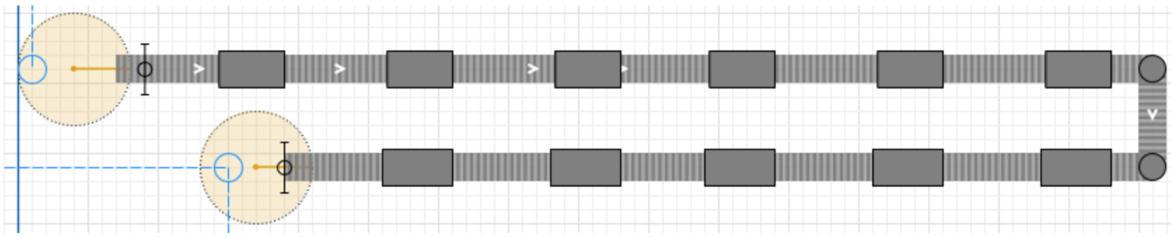


Figure 62 Line representation with Material Handling library tools

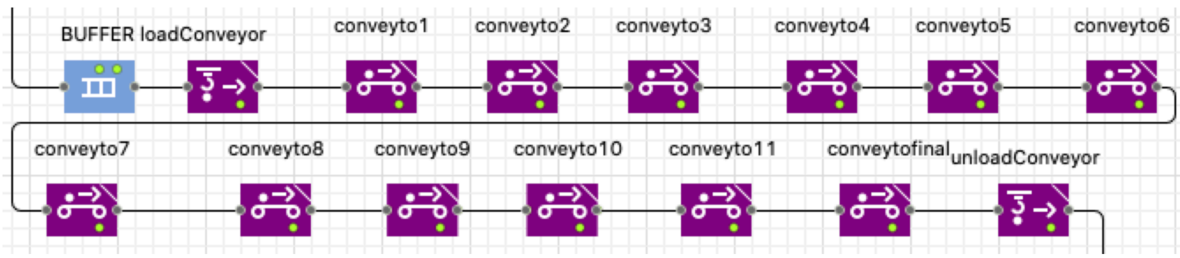


Figure 63 Line representation with Material Handling library blocks

Please open the Anylogic file to start the simulation to capture more detailed animations hereafter represented by an on-process screenshot of the run simulation.

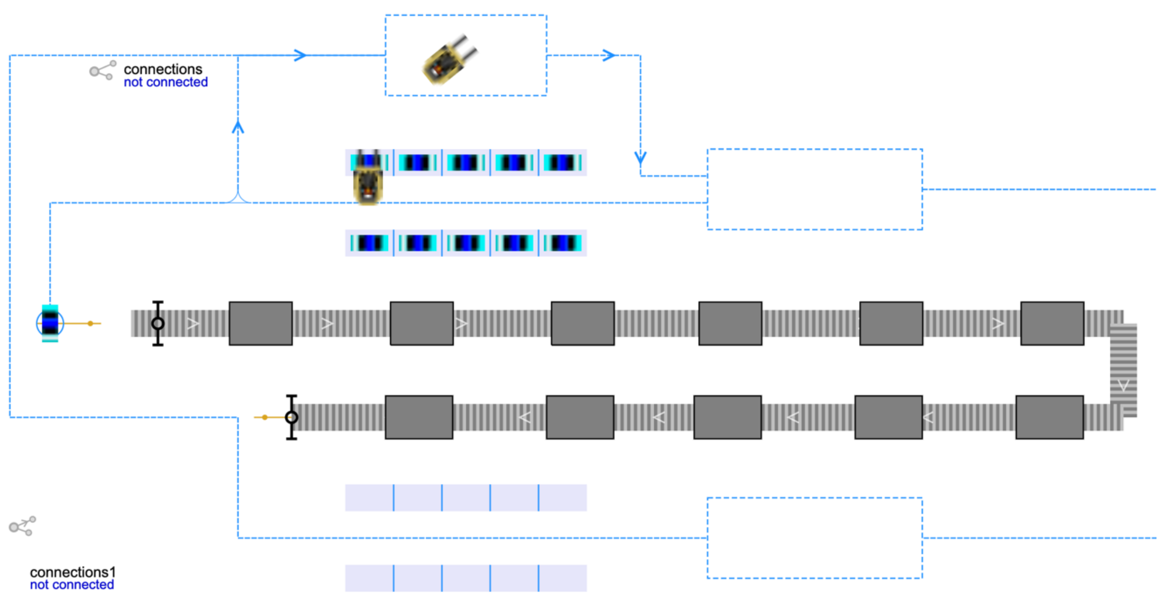


Figure 64 Line operations approximated in the Anylogic environment

Receiving warehouse optimization

For what concerns the incoming and shipping warehouse simulations, only Process Modeling blocks have been used to graphically simulate all the needed operations. This part requires the modeling of two movements: first, the unloading of the truck. Later, the stacks loading, unloading and the car bodies transportations to the queue node where they will later be moved by jib cranes to reach the conveyor.

Please note that the second mentioned material movement in reality represents the first modeled one. In fact, with respect to the first one, it is integrated with the line block, representing a complete operational sequence. Thus, this one will eb addressed first.

The **stacks loading and unloading** along with the **transport to the queue node** is performed by means of a sequence of the blocks Source, rackStore, Delay, rackPick.

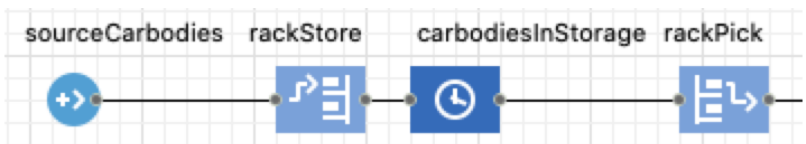


Figure 65 Anylogic blocks for racks loading and unloagind

While Delay and Source blocks characteristics have been already addressed, the remaining two are explained in the following.

Rack Store. The Rack Store blocks in the one in charge of putting agent into a cell of a given pallet rack or rack system. With this, the agent is transported from the current position to the location of the cell, if needed with the help of transport means, meaning moving resources.

At their option, a delay can be associated with putting agents into given cells. These last ones, can be explicitly specified or chosen automatically. When resources are used to move agents, this block seizes them and brings to the location of the agent. Later, it moves them to the cell, executes optional delays, eventually releasing the resource. Of course, this block requires the association of a rack, item taken from the Space Markup palette.

For what concerns the project, it is recalled that just car bodies are simulated and that these are stored on stacks rather than racks. Unluckily, there is no way to represent stacks if not by means of the Queue block. Nonetheless, given the different logical meaning of the block, it has been chosen to exploit this one performing another approximation.

However, the 3D animation does not show such a difference between the real and simulated storage system because of their dimensions and transport means. Remind that forklifts are the exploited material handling tools, and the simulation uses them too.

A Delay block simulates the time car bodies remain stacked in the warehouse before to be moved by means of the Rack Pick logical block. The holding time is ideal, because in the real layout loading and unloading operations are performed in specified time intervals during the weekly working time.

Rack Pick. This last block performs the opposite operation of the Rack Store one, removing agents from a cell in the specified pallet rack or rack system and moving them to the location of destination.

Here too, the operation can be performed with the help of moving resources like forktrucks, and optionally, a delay may be associated with picking the items. If resources are exploited to move agents, Rack Pick block seizes them, brings to the dedicated agent cell location, executes optional delays, attaches the resources to the agent and finally moves the agent to the next destination, releasing the resources. As for the Rack Store block it is necessary to associate a rack or rack system of the Space Markup palette.

Of course, it will be the same associated to the Rack Store block of the given loading and unloading operations sequence.

In the project, this last block is directly linked to the Queue one, that as mentioned, belongs to the line representation yet.

Likewise, dealing with the truck unloading block sequence requires a different dissertation. In this case, the logical sequence is in some way standardized. In fact, when needed, a combination of the block Source, MoveTo and Delay in optimized to either represent a material receiving with truck unloading or material shipment with truck loading. The sequence of the blocks, all belonging to the Process Modeling library, is the next one.

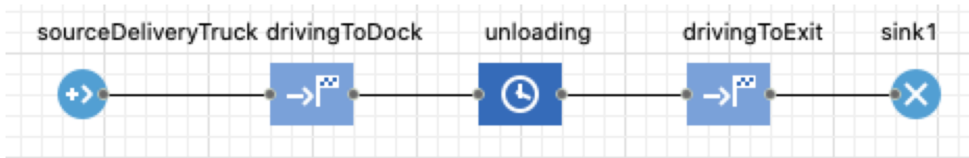


Figure 66 Anylogic simulation for trucks arriving

The only block not explained up to this moment is the MoveTo one.

Move To. The Move To block is in charge of moving agents to a different new location. Whenever resources are attached to the agent, these last one will move with them at the agent speed regardless of the attached resource speed. The destination can be an attractor, node, GIS point, specified agent, point with specified coordinates, and so on. The followed path is generated by the Path Space Markup tool.

While the Resource block generates agents (here, trucks), the Move To block is used to simulate trucks movement in both the shipping and receiving docks. The Delay block simulates the unloading time, while the Sink one is the obvious block sequence end in charge of agents' release.

Please note in this case the blocks do not require to be attached to the main line blocks structure, thus representing standalone operations. Later, they will be linked thanks to the use of the same moving resources, in this case forktrucks.

Java script are either used as "on startup" or "on exit" commands for the synchronization of the trucks' behavior.

Shipping warehouse optimization

Having read the previous chapter, it results way easier to deal with the shipping warehouse optimization design. In fact, both the logical block sequence for items movement inside the plant and truck loading is performed with the same Process Modeling blocks, with similar characteristics of the main parameters. Admittedly, the only difference is the utilization of the PickUp block, explained hereafter:

Pick Up. This block removes agents from a Queue block connected to the input port of the Pick Up one. Moreover, it adds them to the contents of the incoming agent. When an agent arrives at input port, this block iterates through the contents of the queue and selects the agents according to a given mode, like all agents, first N agents, agents for which a condition is true. The whole operation takes no time.

Here it is used as a thinner between the bigger block path and the smaller one, meaning between line and shipping modeling blocks sequence.

Figure 67 Anylogic simulation for trucks leaving the plant

Overall working frame

At the end, the overall working frame resulting from the connection of both Process Modeling and Material Handling libraries blocks and defining the general behavior of the material handling and line operations results in the next logical scheme.

At the top, the longest sequence represents trucks and stacks unloading and loading, such as assembly line operations. The two shorter ones, the trucks behavior.

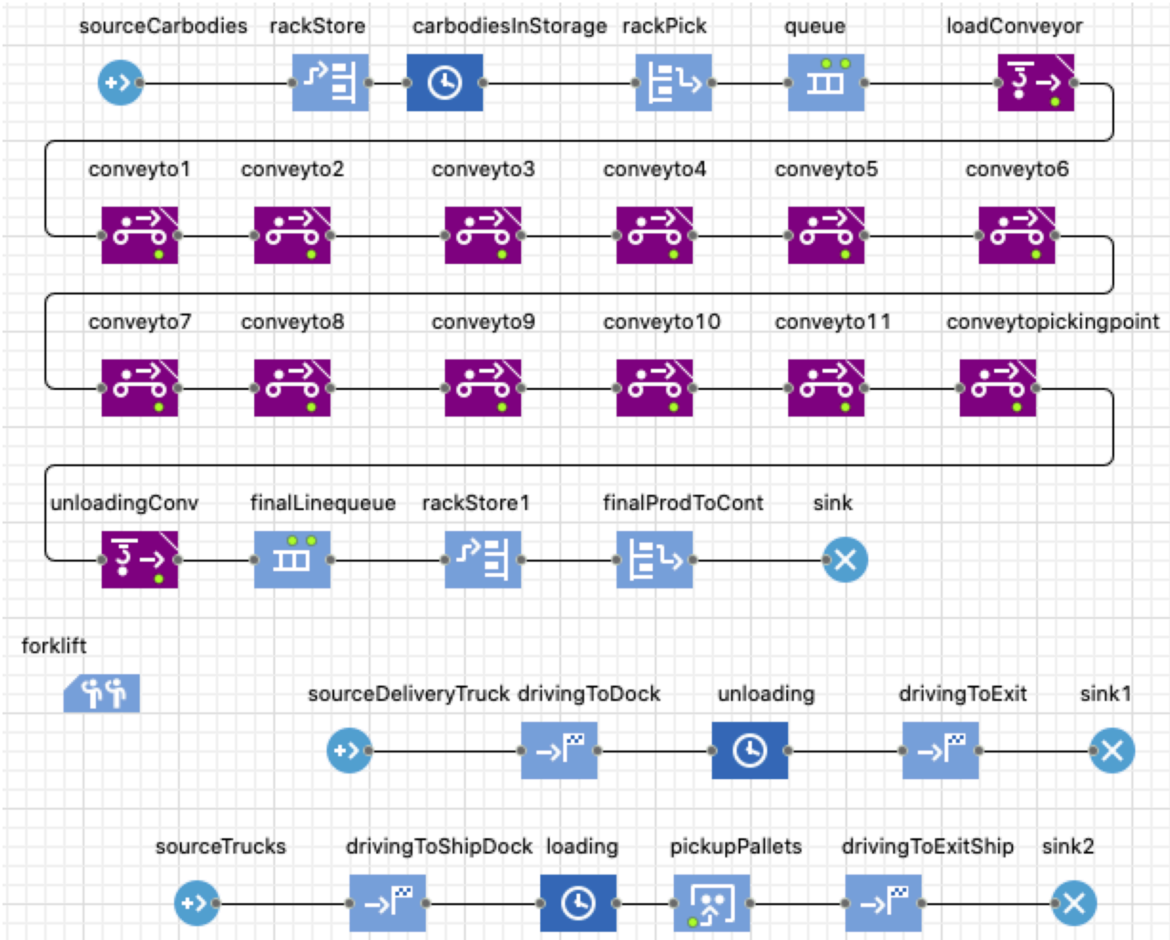


Figure 68 Final Anylogic blocks representation of operations

4.3 Tridimensional simulation

Anylogic, as a powerful software, allows users to graphically represent their work or layout in a tridimensional environment. De facto, all the work done up to this movement has been run with bidimensional simulations, aimed at the logical validation of the plant design. Anyhow, by means of 3D representations, a clearer problem insight can be captured.

Simulation in Anylogic environment

Now, 3D animations are added to the project in order to graphically obtain a complete representation. This phase requires:

- 3D animations implementation to each of the used agents or resources

- Attachment of graphical representation tools to visualize the items once simulation is run.

The first of the two operations has been performed both during and at the end of the 2D implementation of the saπme software. In fact, when defining a given resource, such as a truck of a forklift, 3D animations are taken from the 3D libraries of Anylogic and at a first attempt, run as bidimensional ones.

In reality, they are defined in spatial environment yet. The same holds for the racks, walls and conveyor related items. In fact, the "height" parameter allows a tridimensional development of the structures, ready to be visualized.

The most relevant action to be performed is the positioning of the Presentation palette tools. In fact, by means of the "3D window" tool it will be possible to visualize the plant in a tridimensional way. 3D window has to be positioned on the Anylogic working environment and a "Camera" has be the associated. "Camera" is the name of the tool exploited by the window as an eye giving the spatial perspective of the visualization.

The desired coordinates of the point of view can be copied and paste to fix them as standards during simulation running. Done this, the window can be selected and the 3D representation is ready to be selected.

An example of the chosen 3D perspective is reported hereafter.

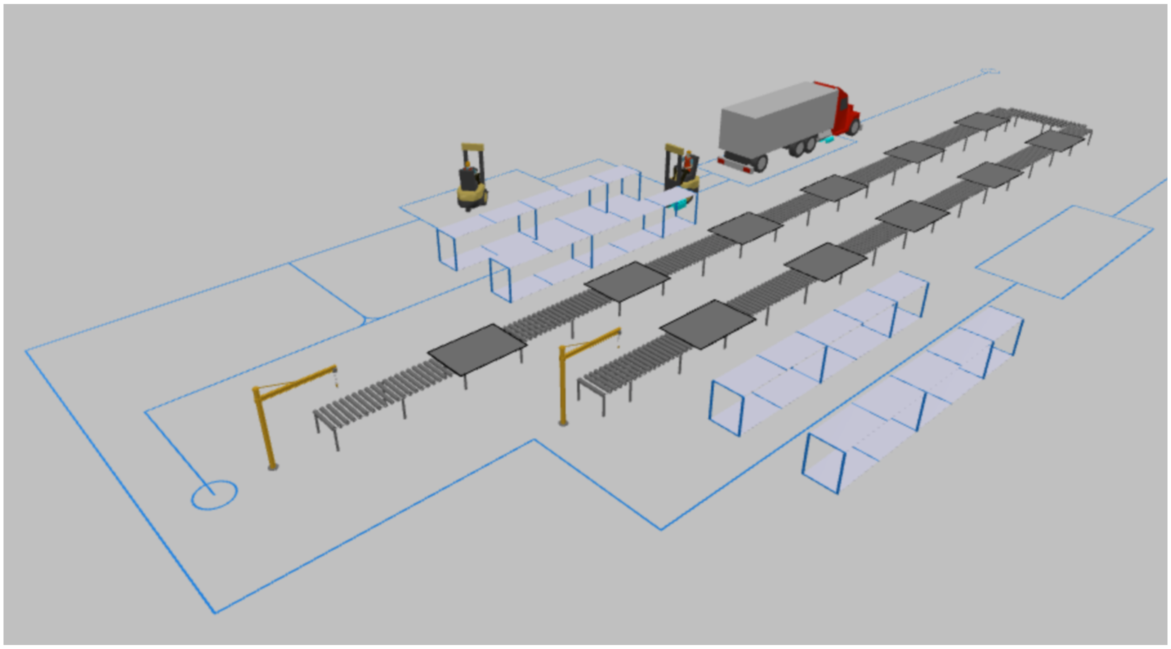


Figure 69 Final 3D line representation in the Anylogic environment

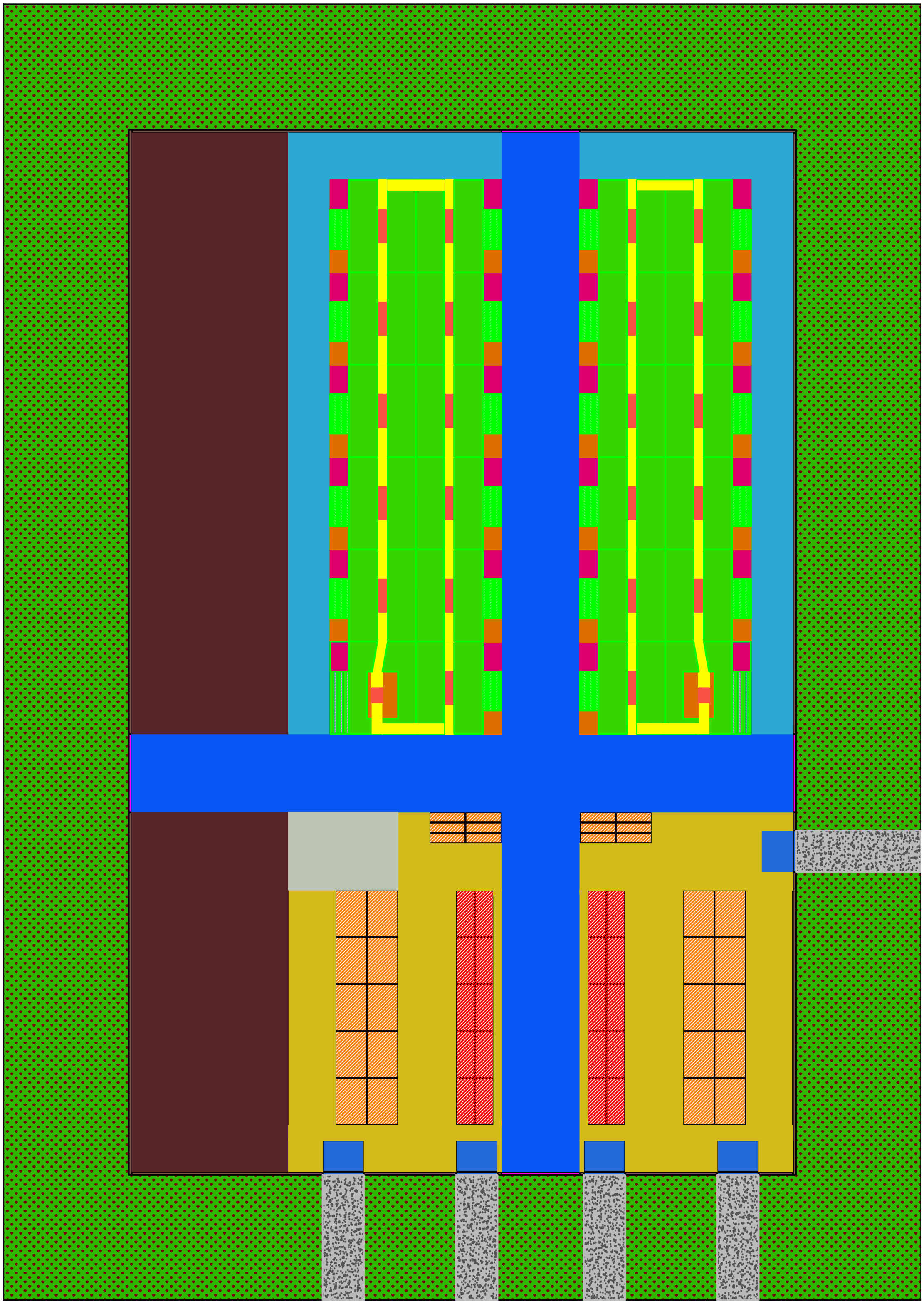
Simulation with plant design

The last part of the work results in the implementation of the previous model in the tridimensional environment with the graphical base coming from the Autocad software.

Please note the base is exactly the same even though the colors representation is slightly different. In fact, in order to avoid all the dashed area that could confuse the user during simulation, solids colors are used. Moreover, a hint to the external area is represented by means of grass and clay texture.

Of course, that will not be the final one but, given the need of simulating track reception and shipment, a rough external area design is provided. The picture used as Anylogic environment background is represented in the following page.

Remind that the external part design, making part of the master plan detailed design, is left as a second more detailed design phase not addressed in this project.



Drawing 3 AutoCAD representation for Anylogic environment base

For the simulation the car bodies dock on the right side of the plant, the right assembly line and the right stacks for car bodies stacks are used. Walls are designed in the 3D environment by means of the tool of the Pedestrian library of Anylogic. Trucks and racks dimensions are adjusted to the drawing design.

Tridimensional animations are added for the assembly station with bench, the worker and a kind of pallet with symbolic carton boxes (remind each pallet hosts a different number of carton boxes of different dimension station by station) exploiting the 3D libraries figures present in the Anylogic software yet.

Reminding all the previously mentioned approximation, the simulation is run. Again, to capture details it is recommend to run the model with the software. Just for a qualitative representation two screenshots of the final layout are reported here after.

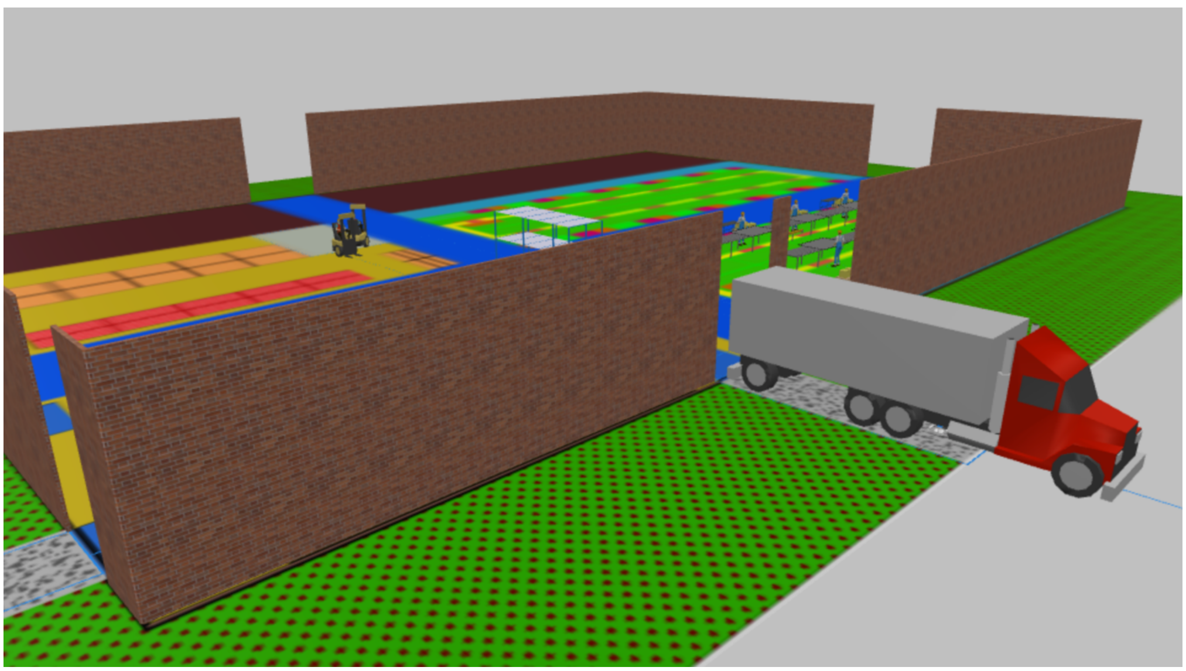


Figure 70 External wall and truck in the Anylogic viewer

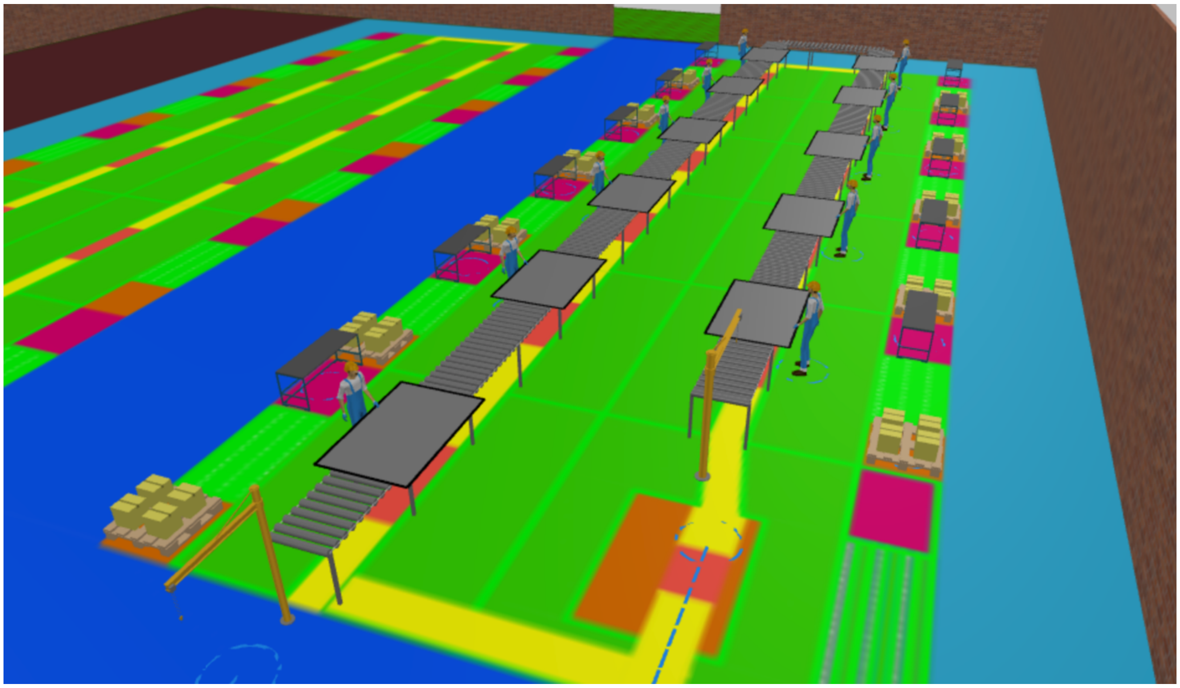


Figure 71 Internal plant assembly line representation in Anylogic viewer

5. Conclusions

This five months project helps the INSIA institute formula student team in understanding the industrial logic behind the business case that is part of the FSAE competition.

In the first part, the plant dimensioning is performed. Starting from the definition of the aggregation level of the modules, passing through the number of workstations for each line, the line balancing and validation is carried out. **The result is two lines**, **symmetrically disposed inside the plant working area, of 11 stations each.**

Moving on, choices concerning the working and storage plant area are done, such as the disposition of the main functional area and the expansion one. In the meanwhile, the economic side is taken into account for a future profitability evaluation. In fact, the economic evaluation is not directly part of this project but this last one sets the stage for a faster evaluation in future design stages.

Following the same logic, the dimensioning of the plant area support functions, entrance and pillars positioning are left to a future more detailed design phase. **The plant working area**, with the expansion one, **results in a side to side dimension of 42,6 m and 66,8 m respectively**.

Parameters for the warehouse and material handling performance analysis show good values for the accounted layouts.

In the second part, after an introduction to the analytic method for variability analysis, the Anylogic "Process modeling" library has been used for line validation and to prove the line is able to sustain certain levels of process variability. Results are coherent and **the line is able to sustain increasing variability in almost all the described cases**.

Eventually, the "Material Handling" Anylogic library is exploited to provide graphical view, both bidimensional and tridimensional, of the designed lines and warehouse area. Of course, approximations are done to allow the software to work properly. Anyhow, the final result is coherent with the outcomes of the previous stages.

At the end, the project leaves a solid base for the economic evaluation that is internally performed by the student team and gives structured ideas for the industrialization of the FSAE car production that can be used to gain competitive advantage in the next years competitions.

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