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Master of Science in Automotive engineering

Master Thesis

Application of an AGV system for material handling to a cellular manufacturing environment: the Valeo case

Candidate:
Giuliano Ferrari

Supervisor:
Dr. Anna Corinna Cagliano

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Abstract

This thesis proposes the application of an automated guided vehicle (AGV) system to a cellular manufacturing environment. It reports the results of a case study conducted in a manufacturing plant in Santena (Italy) that belongs to the Valeo Group, a multinational automotive supplier. The implementation of the AGV technology may be more difficult in such manufacturing environment. There are multiple pick-up points and a large number of different stock-keeping units (around 5,000), with high demand variability and low production volumes.

Valeo currently uses a towing truck system to drain the material outflow from cells in the Santena plant. The referred system has shown to be ineffective: its transporting capacity was poorly explored and many unnecessary displacements were frequently performed, thus having a harmful impact on the activity's labor costs. An alternative system, employing the same equipment, was proposed with the objective of reducing the operational cost. The cells were divided into three groups according to their individual production rates. By serving each group separately, the rearranged towing truck system managed to provide a significant reduction in operational costs but caused a negative impact on the performance.

An AGV solution has been proposed as an alternative system capable of providing a good service level while reducing the operational costs significantly. The proposed solution aimed at providing a good automation level without requiring a large modification of the current plant layout, which should be avoided due to the costs involved. Results from the simulation of the AGV system behavior showed that this technology would allow for an expressive reduction in operational costs while increasing significantly the system's performance. The profitability of the investment was boosted by an incentive program (the so-called Industry 4.0 National Plan) launched by the Italian government for encouraging the acquisition of interconnected technologies. The program offered increased tax deductions for the purchase of this kind of asset, thus reducing the payback period of the investment.

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Undertaking this Master of Science in Politecnico di Torino has been a life-changing experience and it would not have been possible without the help and guidance that I received from many people.

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Introduction

Automated guided vehicles (AGV) have been increasingly employed by the industry in the past decades. The technology is based on vehicles utilized as material handling equipment that operate autonomously in a manufacturing plant, without the need for a human operator. The AGVs are widely used in large-scale production facilities, especially in the automotive market, to increase efficiency and reduce internal transportation costs [1]. The technology meets the current trend within the international industry towards an increasing level of automation of the manufacturing plants. The concept of Industry 4.0 has been also consolidating the idea of a fourth industrial revolution based on "perpetual communication via Internet that allows for a continuous interaction and exchange of information not only between humans (C2C) and human and machine (C2M) but also between the machines themselves (M2M)" [2].

This thesis is based on a work developed in Valeo, a multinational enterprise from the automotive industry, as part of the internship program through which the author had been for six months, between January and June 2017. The analysis has been developed based on the particularities of one of Valeo's plants in Italy, specifically the Santena manufacturing facility.

The use of AGVs in Valeo's plants throughout the world is very significant. In fact, the major part of the company's manufacturing facilities in Europe already employs autonomous vehicles as part of its in-plant logistics processes. The Santena plant, by having a production system with particular characteristics, as subsequently discussed, had not adopted the technology yet, but the company intended to evaluate the implementation of the system in the plant, as a way of increasing its transporting efficiency and reducing the internal logistics costs. At the time the study was held, the Italian government issued a law decree (the so-called Industry 4.0 National Plan) for promoting investments in new industrial equipment, especially in interconnected devices. The decree offered better amortization conditions to companies that invested in these product categories. This incentive made the implementation of an AGV system even more attractive at that time.

This thesis is divided into eight chapters. Chapter 1 is dedicated to a review of the literature on the main topics of the thesis. It is followed by a presentation of the company in which the study was developed (Chapter 2). Chapter 3 analyzes the current material handling scenario in the Santena facility, evaluating the characteristics and particularities of the different systems. An alternative system is then proposed, using the same material handling devices, in a more economical way, reducing the labor costs directly related to the material transportation tasks

(Chapter 4). Finally, an AGV system solution is proposed, having as objective to increase the level of automation of the task, thus increasing performance and decreasing the operational cost (Chapter 5).

The performance of the three previously cited solutions is assessed through a set of simulations, taking into account the constraints and parameters of each system (Chapter 6). A cost-based analysis is then performed, comparing the economic impact on the operation cost by the different solutions (Chapter 7). And, finally, the profitability of the investment in the AGV system is assessed, followed by a conclusion about the best solution according to Valeo's strategical plan (Chapter 8).

This thesis provided Valeo with a complete analysis of the material handling scenario in the Santena plant. It detected some issues on the current way of transporting materials through the plant, and proposed alternative systems to overcome the detected problems. As it will be discussed in the following chapters, we provided an alternative system capable of increasing significantly the performance of the transportation task while reducing expressively the operational cost of the studied activity.

Chapter 1

Theory background

This chapter is dedicated to a review of the literature on the main topics of the thesis. This review aims to highlight the main characteristics of a cellular manufacturing system and its related technologies, as well as describing the main issues related to the design of such system. Finally, the automated guided vehicle (AGV) technology is described in a deeper way, since it is the focus of the research. The papers and studies mentioned in this chapter aim to explore the main characteristics of an AGV system that should be taken care when designing it, as well as introducing new related technological trends.

1.1 Cellular manufacturing

1.1.1 Main characteristics

Cellular manufacturing (CM) is based on the concepts of Group Technology (GT). The ideas of GT were firstly introduced by Mitrofanov in the 1960s. Late in the 1920s, researchers started to identify reduced transportation costs if the departments of manufacturing plants would be oriented towards standardized products [3]. It was only in 1966 that Mitrofanov [4] defined the principles of GT, which were further explored by Burbidge [5] in 1971. The theory was based on classifying parts that go through a company's manufacturing processes, in such a way that parts with similar characteristics are produced jointly, going through similar assembling or manufacturing processes. Overall, GT relies on the principle that "similar things should be done similarly". Within the production context, "things" could be interpreted as parts and products, while "similarly" would refer to fabrication, assembly, and production processes, although the GT principles could be also applied to other activities within the company's environment [3].

The cellular manufacturing system (CMS) is derived from the principles of GT. It consists of grouping a set of machines of related technologies dedicated to the production of a family of parts. This type of manufacturing layout aims to arrange the machines so to facilitate a continuous production flow in small lots of medium to high number of different products. The goal of this arrangement is to provide the necessary flexibility to the production process of different parts while seeking to achieve the same level of productivity of large-scale production systems. This type of layout aims at the reduction of the total set-up time of the machines, given the fact that, as machines work with similar parts, the required additional set-ups and their single duration tend to decrease [3].

The benefits of applying CMS to the production system has been evaluated by many researchers. Wemmerlov and Hyer [6] measured the results of the employment of CMS in 32 companies in the United States in 1989. The authors identified significant reductions in throughput time, work-in-progress inventory, material handling cost and set-up time, as well as improvements in space utilization, machine utilization, material flow, and quality. Heragu [7], Selim *et al.* [8], and Mansouri *et al.* [9] also suggest good effects as consequence of CMS: reductions in worker and material scrap, rework, and production costs, while increasing production control and flexibility.

The use of workcells provides a compact layout, by placing machines dedicated to a family of products close to each other. This implies in a reduction of the parts traveling distance between machines in comparison to a functional layout. The communication between operators is facilitated, since they work close to each other, enhancing teamwork and the alignment of processes. Supervision checks can also be performed in an easier way because of the possibility of tracking the path of a part in a compact portion of the production floor area. On the other hand, CMS requires a higher level of training of the employees, since the flexibility is one of the pillars of this production layout and so operators may need to perform a wider range of tasks [10].

The CMS allows for a one-piece flow of material, that is, operators handle one part at a time, in contrast to the traditional batch production, in which a batch of parts is worked in sequence by the same machine. Workcells show advantages compared to the batch production system in terms of lower lead times and smaller size of buffers between stations, working practically as a just-in-time system. Workcells also allow for an easier error detection, since an error may be identified as soon as it occurs, while in a batch production system it usually can be detected only at the end of a lot [3].

1.1.2 The Cell Formation Problem

The procedure of designing workcells is focused on searching for patterns on the path of parts between machines. Each individual part produced by a company goes through a sequence of machines that transform it into the desired finished product. The sequence of machines is determined individually, and the problem is then to identify parts that go through similar machine sequence. Cells should be designed so that the whole production process of a range of similar products can be performed by the machines within the workcell. The issue when designing the cells is then to identify families of parts whose production process is performed by the same set of machines with similar technological characteristics. This problem is called in the literature as the Cell Formation Problem (CFP) [11].

An effective and illustrative tool to identify part families is the Product Family Matrix Analysis (PFMA). It consists of representing the sequence of machines through which the different parts go into a matrix [12]. Figure 1.1 illustrates the

PFMA of a fictional set of products. The machines through which each part goes are indicated by an "X" sign.

PART	MACHINE 1	2	3	4	5	6	7	8	9	10	11	12
A	X	X		X				X		X		
B					X		X				X	X
C			X			X			X			
D	X	X		X				X		X		
E					X						X	X
F	X			X				X				
G			X			X			X			
H							X				X	X

Figure 1.1: The PFMA for a fictional set of products [13]

By rearranging the position of machines on the matrix, it is possible to group parts with similar production processes. Figure 1.2 provides a possible solution to the fictional PFMA. Note that machines are grouped into three different cells, each of them producing a defined set of finished goods.

PART	MACHINE 1	2	4	8	10	3	6	9	5	7	11	12
A	X	X	X	X	X							
D	X	X	X	X	X							
F	X		X	X								
C						X	X	X				
G						X	X	X				
B									X	X	X	X
H										X	X	X
E									X		X	X

Cell 1

Cell 2

Cell 3

Figure 1.2: A possible rearranged PFMA for a fictional set of products [13]

The previous example is here used to illustrate the CFP. On the example, it has not been mentioned the methodology employed for the identification of part families - in this case, it was done by trial and error. This example, though, might be too simple compared to the complexity of many production facilities, particularly in terms of the number of different stock-keeping units (SKUs). As the number of machines and parts involved increases, it is increasingly more difficult to identify part families. For that reason, CFP has been the object of study for many years and different approaches to the problem have been developed and evaluated. Burbidge [14] developed the first methodology to solve the CFP. His production-based approach aims at grouping parts that share common processing routes. By utilizing machine-part combination matrices consisting of binary coefficients that identify the part routing, similar to the PFMA, this study defines a methodology to rearrange the matrix in order to identify machine-part families. This method, though, may be difficult to implement for a large number of different SKUs. From this viewpoint, a methodology widely used in the following years was developed and named as the Similarity Coefficient Method (SCM), which is based on the application of clustering techniques to the part families identification problem. The method was deeply discussed by Seifoddini [15], Chow, and Hawaleshka [16]. The intensive use of this methodology is due to its flexibility, simplicity, and suitability to computer applications. Researches in the following years aimed at computation velocity reduction and the consequent possibility of application to large-scale industrial systems, as discussed by Chen and Cheng [17].

More recent studies were developed with the objective of enhancing the CFP solution process. In 2000, Mak *et al.* [11] proposed an adaptive genetic approach capable of determining the optimal solution to the CFP, based on the ideas of the genetic approach that was firstly introduced by Goldberg [18]. The genetic approach is based on the sequencing of product-machine combination in the PFMA so to maximize the bond energy of the matrix. Overall, as highlighted by Arabie and Hubert [19], the objective is to rearrange machines and parts in the PFMA in such a way that each position of the matrix is numerically as close as possible to its four neighboring positions. The application of the bond energy approach to the CFP provided an effective tool for finding its optimal solution. Mak's contribution was to develop an adaptive system that adjusts the genetic parameters, increasing significantly the performance of the search process for the optimal solution.

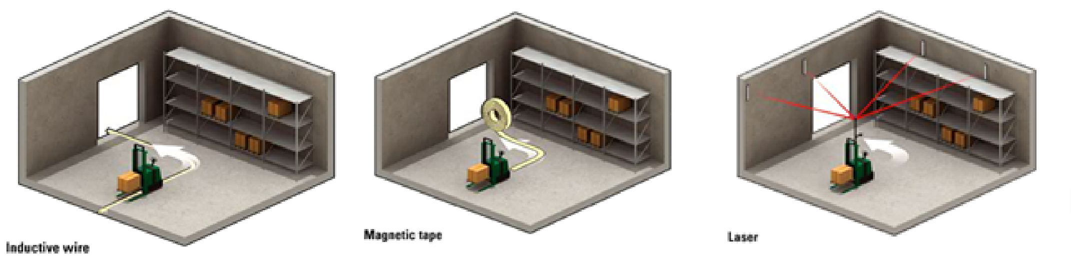
The genetic approach was further explored by Gonçalves and Resende [20], combining the genetic approach with local search heuristic to increase the grouping efficacy of the algorithm. A few years later, Mahdavi *et al.* [21] published an article about the application of the genetic approach to the CFP based on cell utilization concept, introducing a new mathematical model based on Gonçalves and Resende's article and capable of delivering higher computational performance with respect to the other literature models.

1.2 Automated guided vehicle (AGV) systems

1.2.1 Main characteristics

AGVs are self-driven vehicles employed as material handling system (MHS) in many manufacturing operations worldwide. They are most commonly used for material transport between workstations and storing areas in manufacturing plants, however, its application is not restricted exclusively to the industry. AGVs are currently employed in alternative environments, such as mail distribution centers, laundry facilities, hospitals, and prisons [22] [23]. The first time AGVs were employed in large scale was in 1974 by the Swedish automotive company Volvo [22]. In the following decades, this technology has been significantly developed and improved, especially in terms of efficiency, flexibility, and safety. Currently, the main market sectors that employ AGV systems are Automotive, Food and Beverage, Aerospace, Healthcare and Pharmaceuticals, and Retail [24].

AGVs are battery-powered vehicles whose movements are controlled by a central computer unit. As an autonomous system, they do not require any human assistance for transporting materials between workpoints, although human cooperation is also compatible with this kind of MHS. AGVs can be divided into two types, according to its guidance system: free-ranging and path-restricted vehicles. In the first case, the vehicle can move freely in the plant by using dead-reckoning (AGV's location estimated by odometry and orientation equipment [25]) or lighting devices (laser or infrared) that estimate vehicle's position according to light streams emitted by it and reflected by specific apparatus on the walls. This alternative may also be enhanced by a grid pattern on the plant's floor (either magnetic or optically scanned) that helps with positioning calibration. In the second case, AGV's movements are restricted by a defined network of path segments. The paths are usually determined by two possible systems: induction wires buried in the floor and scanned by means of an induction receiver; or painted tracks (or even tapes) which are optically scanned by the AGV [26]. Figure 1.3 shows some of the different guidance systems that can be employed in an AGV system.



(a) Buried wire (b) Magnetic tape (c) Laser scanner

Figure 1.3: Illustration of three different guidance system alternatives for AGVs [27]

AGV systems can provide many advantages with respect to other material handling equipment alternatives, such as manually pushed carts, forklifts, and conveyors:

- AGVs provide a high level of flexibility, due to the fact that its paths can be easily reconfigured with low cost and time required, meeting new demands or plant expansions [23].

- AGVs occupy a plant's area only when temporarily passing through it, performing an operation or parking, thus the vehicles do not require a dedicated area. This provides a space utilization advantage over conveyors, which continuously occupy a specific portion of the plant area. AGV's workspaces can be shared, for example, with forklift and even pedestrian aisles, thus increasing the overall space utilization [22].

- AGVs increase the overall safety level of the plant, because of the many embedded safety devices: light and sound based warnings are constantly emitted so to alert operators to the presence of vehicles nearby; obstacle sensors perceive the presence of people or objects on the AGV's path, thus stopping it if any obstacle is noticed. Additionally, AGVs eliminate the possibility of human errors, quite common in forklifts operations [22].

- Industry has increasingly invested in the automation of production facilities worldwide. These investments are motivated by the market tendency of costs related to two alternative means of production: operators and machines. United States' statistics show that, in the past three decades, labor costs have increased extremely (in fact, by comparing the years of 1990 and 2010, it doubled) while the cost of automation devices have significantly decreased (practically cut by half in the same period) [28], as indicates Figure 1.4. Therefore, although AGVs may present a significantly higher acquisition cost with respect to forklifts and other alternative material handling devices, the investment is usually recouped in a short period of time due to the reduction in operational costs (by eliminating partially or completely the labor costs directly involved with the material handling activity), especially in operations with multiple workshifts [22].

- As discussed in the previous items, manufacturing plants have increased their automation level in the past years. An important issue to be dealt with is the human-robot interface, i.e. how operators and machines would work simultaneously and collaboratively. From this viewpoint, AGVs facilitate the interface with other automated systems [22], both in terms of reducing interaction times and eliminating the need for human-safety devices (if the interaction with operators is completely excluded).

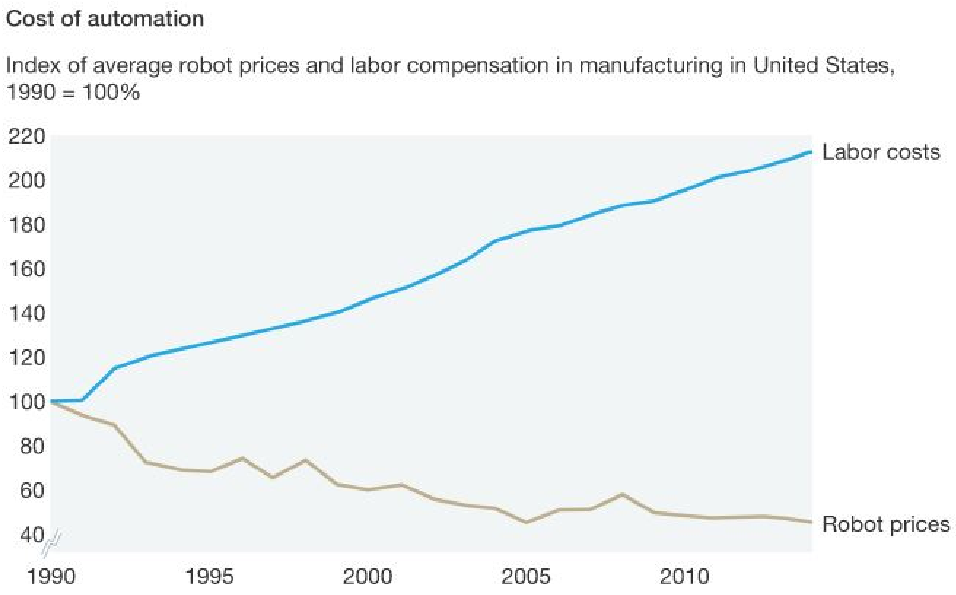


Figure 1.4: Evolution of the average labor costs and robot prices in the United States from year 1990 [28]

Motivated by the tendency of labor and automation costs shown in Figure 1.4, the forecasts for the next decade of the AGV market are very enthusiastic for automation companies. Figure 1.5 shows the forecast of the AGV market size until year 2024 [24]. According to the Grand View Research, the AGV market is expected to double its size in the referred decade.

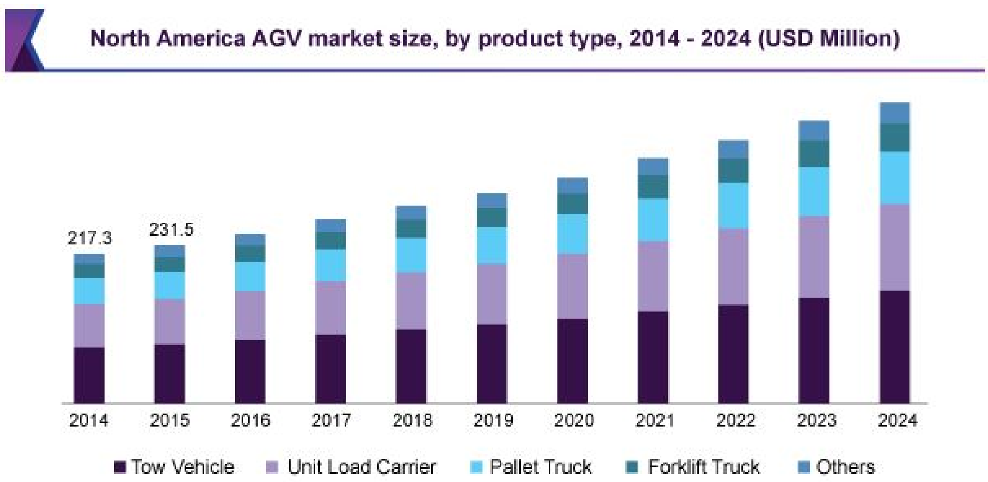


Figure 1.5: Forecast of the AGV market size in North America for the 2014-2024 decade (2014 and 2015 figures are consolidated) [24]

1.2.2 Main types

The main types of AGVs can be listed as follows.

(1) Tugger AGV: this type of AGV is designed to tow a set of trailers or wagons, which are mechanically attached to the vehicle. An example of this AGV type is shown in Figure 1.6. The trailers are pulled by the AGV, forming a train system. Although this was the first AGV type introduced, it is still frequently employed in automated systems. The tugger AGV can be used in a wide range of applications. These vehicles can be found in the market with capacities from a few hundred kilograms up to 30 tons.

Figure 1.6: Tugger AGV by JBT [29]

(2) Unit load AGV: these vehicles are equipped with a deck on which unit loads are placed. This type of AGV, indicated in Figure 1.7, may allow for automatic loading and unloading of materials. This may be achieved by powered rollers, belt and chain conveyors, or gravity flow rollers. This application offers an easy interface with automated storage and retrieval system (AR/AS).

Figure 1.7: Unit load AGV in an assembly line [30]

(3) Pallet truck: this type of AGV is conceived to transport palletized loads in manufacturing facilities. The solution is illustrated in Figure 1.8. Inspired by the conventional pallet jack, this AGV application allows for limited vertical displacement of the load, reaching pallets on racks or shelves at a small height. Its transporting capacity can vary from few hundred kilograms to several tons.

Figure 1.8: Pallet truck AGV by JBT [31]

(4) Forklift AGV: this AGV type is inspired by the conventional forklifts, providing a full automation of the transporting device. Examples of this solution are shown in Figure 1.9. The forklift AGV is designed to provide both horizontal and vertical movement of the load. They can also be configured to stack loads in racks.

Figure 1.9: Forklift AGV by Egemin Dematic [32]

(5) Light load AGV: these vehicles are designed for the transportation of light loads (usually with a capacity of up to 200 kg). Figure 1.10 shows an example of this type of AGV. It is commonly used to move small parts or light boxes in manufacturing facilities. Due to its small dimensions, it is usually employed in plants with limited space.

Figure 1.10: Light load AGV by SSI Schaefer [33]

1.2.3 AGV system design parameters

The design of an AGV system can be very complex due to the high number of different variables involved, as well as the difficulty of predicting material transportation demands. The most critical issues to be held when designing an AGV system can be listed as follows: design of the guidepath layout, number of vehicles required, vehicle scheduling and dispatching, location of pick-up and drop-off stations, and collision avoidance in routing definition [22] [34].

The guidepath layout has an expressive influence on the complexity of the AGV system control. Manufacturing systems are increasing in size and complexity, and thus the AGV control system for vehicle coordination has increased in complexity to the same extent. Therefore, the guidepath layout problem has been studied as means to simplify the controlling system [35]. The main AGV guidepath layout configurations discussed in the literature are the *conventional* [36], *tandem* [37] [38] [39], *single-loop* [40], and *bi-directional shortest-path* [41] [42].

In a conventional guidepath layout, all vehicles are allowed to drive freely and serve any workstation [43] (Figure 1.11) - this implies in a more complex control system as the number of vehicles increases.

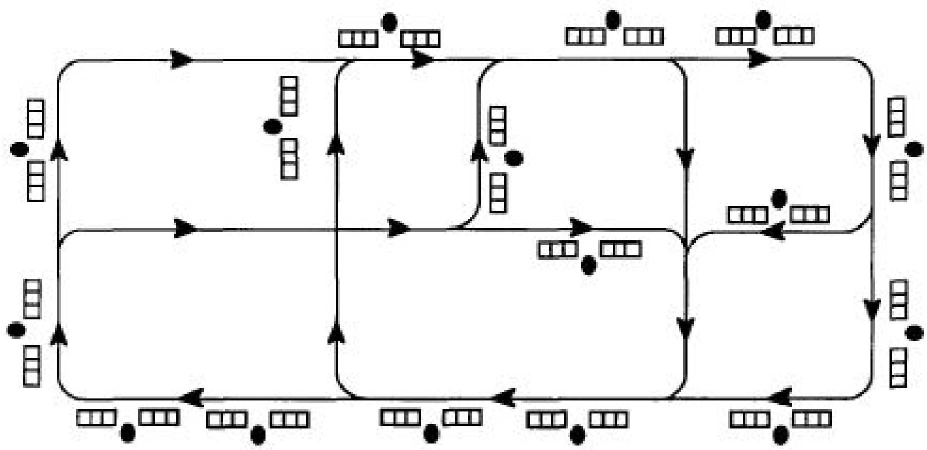


Figure 1.11: Example of a conventional AGV guidepath layout [43]

The tandem configuration is based on partitioning the manufacturing area into non-overlapping zones in which a single dedicated AGV operates (Figure 1.12). Tandem layouts solve the routing problem by eliminating any possible traffic issues (since in each zone a single vehicle has to be handled) while providing flexibility due to the fact that zones can be easily added or modified without affecting other zones. The main limitation of the tandem configuration is that a load may be handled by several AGVs until the drop-off point is reached. Hence, transfer points have to be created, requiring additional floor space and investments. Also, transferring points may represent additional delays in the material delivery. [43]

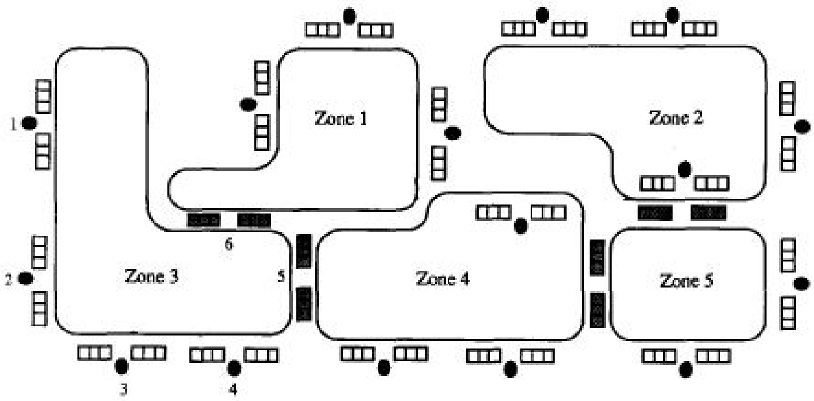
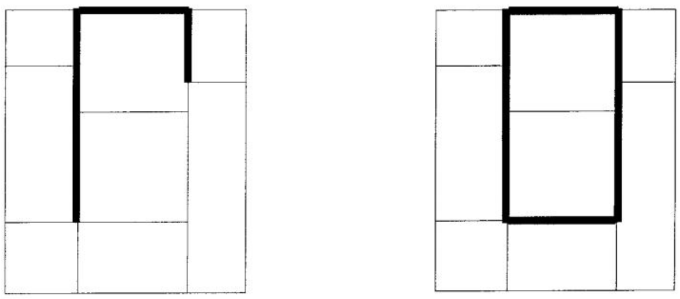


Figure 1.12: Example of a tandem AGV guidepath layout [43]

Figure 1.13a illustrates, for a fictitious plant layout, the shortest path that touches all the departments. This configuration consists in finding the shortest guidepath that passes by all the workstations on the plant. The solution aims at maximizing efficiency because vehicles always drive through the shortest path between the origin and the destination station [35]. Finally, the single-loop configuration (Figure 1.13b) is based on finding the shortest closed circuit that passes by all workstations. In contrast to the previous configuration, it provides the lowest controlling complexity because all vehicles travel in the same direction, thus reducing traffic problems [35].



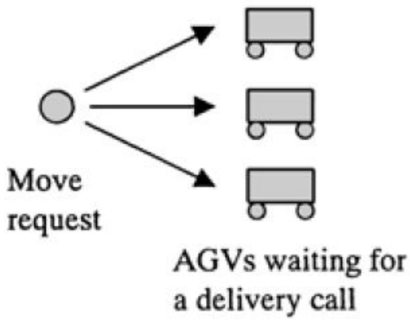
(a) Shortest path

(b) Single loop

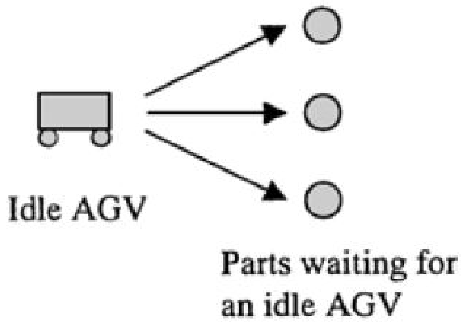
Figure 1.13: Illustration of shortest-path and single-loop AGV guidepath layout [35]

The scheduling and routing of the AGV, as mentioned before, are also critical factors in the design of such a system. Scheduling refers to assigning a set of vehicles to perform material pick-up and drop-off activities under certain scheduling constraints. Routing, on the other hand, consists in finding the most suitable, conflict-free path through which each vehicle should drive in order to achieve the objectives defined in the scheduling phase [1]. The complexity of the routing problem grows as the AGV fleet size increases, and also if AGVs are free-ranging type, or the transporting requests are not easily predictable (random flexible manufacturing systems [44]).

There are two possible situations when a pickup order is issued: 1) one or more AGVs are available; or 2) all vehicles are busy, thus not available. The first case is called in the literature as *machine-initiated dispatching*, in which a central control unit determines a vehicle to perform the required task. In the second case, known as *vehicle-initiated dispatching*, the transporting order is put in a queue of pending pickup orders; as soon as a vehicle is idle, one of the queued orders is assigned to it [34]. Figure 1.14 illustrates both situations.



(a) Machine-initiated dispatching



(b) Vehicle-initiated dispatching

Figure 1.14: Illustration of two AGV dispatching [34]

The selection of a vehicle to execute the pickup order (in machine-initiated dispatching) or the first queued transporting order to be carried out (in vehicle-initiated dispatching) is to be made by the central controller according to a predefined rule. Koo and Jang [34] mention the most common machine-initiated dispatching rules ("random vehicle, nearest vehicle, farthest vehicle, longest idle vehicle, and least utilized vehicle") and vehicle-initiated ones ("random machine, first-call-first-served, shortest travel time, part arrival time, maximum outgoing queue size, and minimum remaining outgoing queue space"). Vehicle utilization affects the choice of dispatching rules (here, the utilization is defined as the probability that a vehicle is busy). If AGVs are highly utilized, vehicle-initiated dispatching is more likely to occur. With low AGV utilization, though, machine-initiated dispatching is more frequently used [34].

The vehicle fleet size problem has been the object of research in the AGV field. Fleet size estimation studies can be divided into deterministic and stochastic models. In deterministic models, the material transportation demand is previously known, while in stochastic ones, pickup orders are issued randomly in time, thus transporting demand is unknown and vehicles are dispatched in real-time [45]. The assessment of the fleet size can also be performed by a simulation approach.

Chapter 2

Company presentation

This chapter is dedicated to a presentation of the company on which the subject of the thesis is based. The presentation aims to show Valeo's main characteristics in its different hierarchical levels, from the main company to its business groups, getting into more details about the specific manufacturing plant in which this project is executed.

A brief presentation of the company's portfolio is followed by a list of its main clients. Valeo's activities in Italy are also described, as well as Santena's facility.

2.1 Valeo Group

Valeo defines itself as 'a global automotive supplier and technology company that designs innovative solutions for smart mobility' [46]. Founded in 1923 in Saint-Ouen, a suburb of Paris, France, the company's portfolio was initially focused on brake linings and clutch facings. It was only in the 1960s that Valeo started a diversification process, exploring the markets of braking, thermal, lighting, and electrical systems. From the 1980s, the company started an aggressive expansion strategy based on the acquisition of international sites [47].

Valeo's current strategic focus is to supply innovative solutions that provide CO_2 emission reduction and intuitive driving technologies. The Stop-Start system, which automatically turns the engine off when a vehicle is stopped, and Mild-hybrid technology, a set of hybrid solutions that enables fuel consumption reduction, are some examples of innovative technologies developed by the company in the pollutant emissions reduction field, while driving assistance systems such as obstacle detection and automated parking, as well as autonomous driving, are part of the company's portfolio in intuitive driving [46].

The recent geographic expansion strategy of the company aims to accelerate the growth in high-potential regions, especially in Asia and emerging countries. Valeo, as a global company, sets as an objective to build up new production facilities locally to meet surging demand in new markets, such as China. In fact, by 2020, the company expects that Asia would represent more than one-third of its sales, with China accounting for 20% [46].

Valeo has 91,800 employees working in 155 production units, 15 distribution platforms and 58 Research and Development (R&D) centers allocated in 32 worldwide countries, which are indicated in Figure 2.1. Its sales in 2016 summed up €16.5 billion, while €1.6 billion were reinvested in R&D [46].

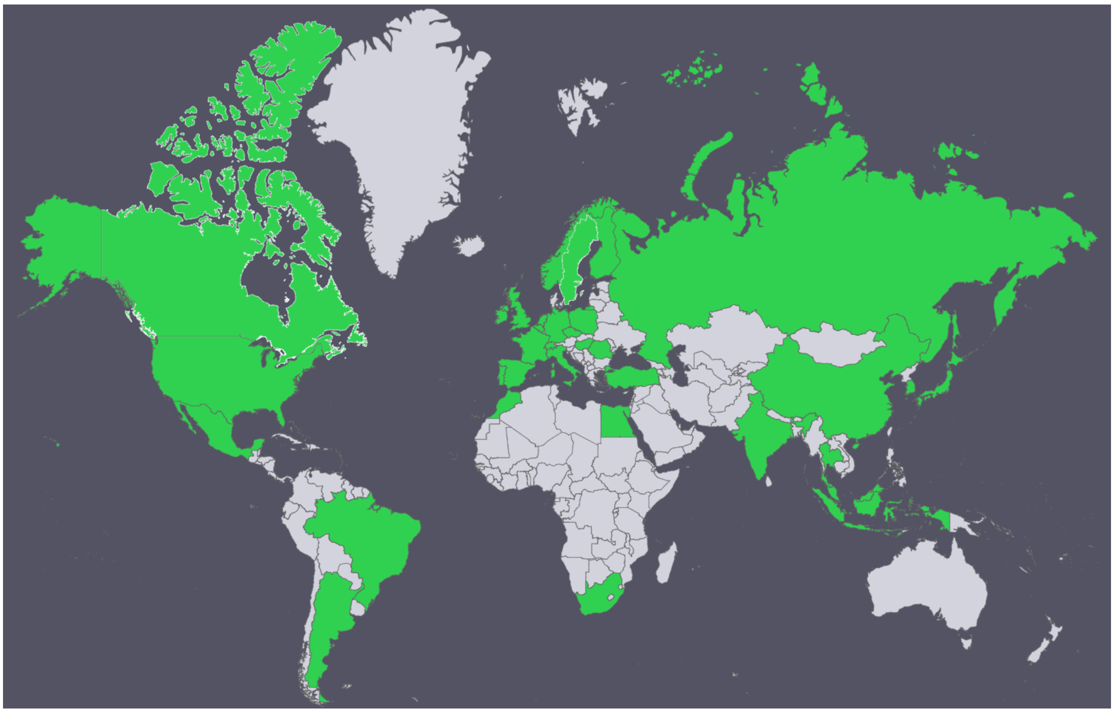


Figure 2.1: Footprint of Valeo's operation around the world (indicated by the green color)

Valeo's set of clients include all major players in the automotive market from all around the world, comprising either automotive suppliers or automakers. Some of its major clients are Volkswagen Group, BMW Group, General Motors, FCA Group, Hyundai Motors, Daimler, and Toyota Motor.

Valeo is made up of four Business Groups and an aftermarket activity, namely [46]:

1. **Comfort and Driving Assistance Systems (CDA)**: the group focuses its activities on developing a large range of sensors, actuators, switches and intelligent solutions that improve vehicle safety and comfort. Its portfolio has three subdivisions [46]:

   - *Driving Assistance Systems*: Valeo designs a set of sensors, radars, and cameras that are used to detect obstacles around the vehicle in order to provide all the information the driver needs when parking. 360Vue®, as illustrated in Figure 2.2a, is an example of this segment of CDA'a activities: this system collects data from four miniature cameras placed on the vehicle and merge the images into a 3-dimensional image of the environment, providing a top view of the car's positioning. This feature makes parking a quite simple task.

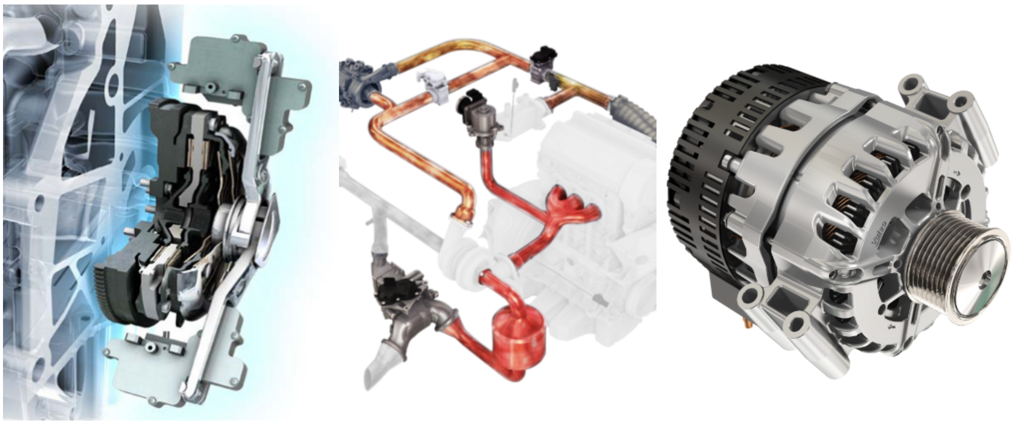
(a) 360Vue® (b) The smart faceplate (c) Valeo InBlue®

Figure 2.2: Examples of Valeo CDA's automotive solutions

- *Interior Controls*: the company uses its extensive experience in the human-machine interface to design innovative solutions that include switches, displays, and sensors dedicated to controlling vehicle interior features (such as air-conditioning, sound system, heating system, entertainment modules, etc.), following the concept of intuitive driving. Figure 2.2b shows the Smart faceplate, a module made up of a display and switches that control vehicle interior systems in a simple, intuitive way even if the number of functions to operate is increasingly high.
- *Connected car*: the segment provides a wide range of communication options for drivers from short-range (unlocking vehicle and starting engine without taking the key out of a pocket - the Valeo InBlue®solution, illustrated in Figure 2.2c) to long-range connectivity solutions (connection with mobile phone networks), focusing on the concept of the Internet of Things.

2. **Powertrain Systems (PTS)**: the aim of the group is to provide powertrain solutions that offer CO_2 emissions and fuel consumption reduction while maintaining or improving the engine performance. Valeo PTS offers three lines of products [46]:

   - *Transmissions Automation*: the automation of transmission modules is a global trend. Valeo PTS offers automatic transmissions, automated manual transmissions, and dual clutch transmissions to this growing market with innovative solutions that aim fuel consumption reduction and driving comfort. Dual Dry Clutch, as in Figure 2.3a, is an example of this segment of PTS's portfolio: it combines the low drag of a dry clutch and the high efficiency of a manual gearbox, increasing its efficiency.
   - *Clean engine*: this line of products is dedicated to the air circulation focusing engine efficiency and CO_2 emissions reduction. Figure 2.3b shows a scheme of some of the segment's solutions: Exhaust Gas Recir-



(a) Dual Dry Clutch (b) EGR valve with intake module, WCAC and electric supercharger (c) 48V Starter Generator

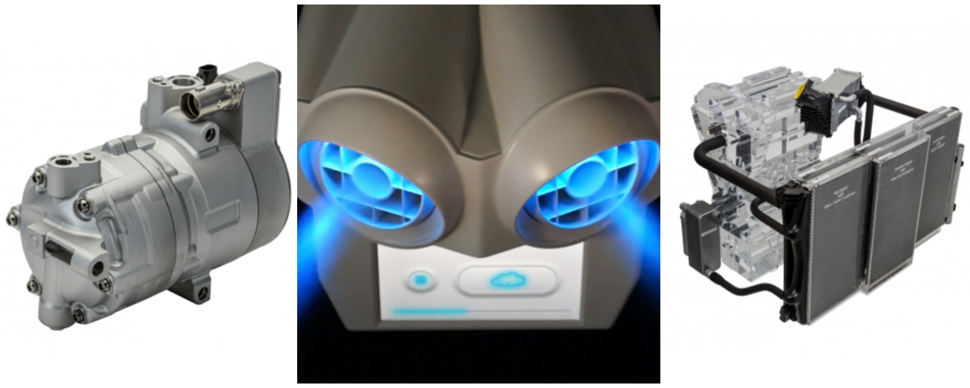
Figure 2.3: Examples of Valeo PTS's automotive solutions

culation (EGR) valve with intake module, Water Charge Air Cooling (WCAC) module, and electric supercharger.

- *Electrification*: this segment provides customized solutions for any level of electrification, from mild hybrid to full electric driving. Valeo participates in a joint venture with Siemens on the full electric project, guaranteeing the high quality of its products. Figure 2.3c shows the 48V starter generator installed on one of the company's hybrid solutions.

3. **Thermal Systems (THS)**: the group designs and develops a large portfolio of components, modules, and systems that manage the thermal state of the engine. Those systems are designed to optimize operational conditions of the engine and provide adequate temperature and humidity to driver's comfort. The THS Business Group divides its activities into three segments [46]:

    - *Electrification*: Valeo offers a set of thermal management modules for all levels of car electrification, in response to the market demand for pollutant emission reduction. The Electrically Driven Compressor (EDC), as illustrated in Figure 2.4a, is specifically designed to comply with the requirements of hybrid and electric vehicles, providing high cooling capacity for the cabin and battery thermal management.
    - *Interior Ambiance Design*: this branch of THS's portfolio focuses on providing comfort and pleasure to passengers inside the cabin, offering a thermal control system that adapts to different temperature conditions. The AquAIRius®Cooling Mist Diffuser, illustrated in Figure 2.4b as an example of this segment's products, equips the air-conditioning (A/C) system with a diffuser that introduces micro water droplets on the air stream for passengers' comfort and humidity balance in the cabin.



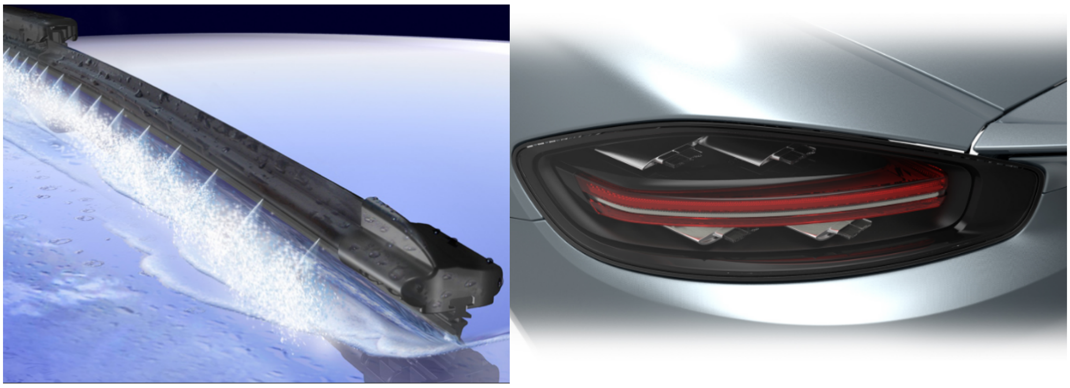
(a) Electrically Driven Compressor (EDC) (b) AquAIRius®Cooling Mist Diffuser (c) Flat and Light Engine Cooling Module

Figure 2.4: Examples of Valeo THS's automotive solutions

- *Internal Combustion Engine (ICE) Emissions Reduction*: with the focus on reducing CO_2 and NO_x emissions as well as fuel consumption on ICE vehicles, Valeo solutions aim at four main axes: A/C efficiency, vehicle lightweight, aerodynamic improvements and engine thermal management. Figure 2.4c shows the Flat and Light Engine Cooling Module, composed of radiators, condensers and a fan whose function is to avoid engine overheating. This is an example of a solution that combines all four main axes of this segment of THS's activities.

4. **Visibility Systems (VIS)**: the group designs and manufactures innovating lighting and wiper solutions that improve driver's comfort and vehicle safety under bad weather conditions. Valeo VIS is made up of two Product Groups [46]:

   - *Lighting Systems*: in a partnership with Ichikoh, a Japanese company with large experience in the lighting area, Valeo designs and develops interior and exterior lighting systems with refined style and high level of reliability and innovation, following the needs of vehicle's market trends. Figure 2.5b shows the LED rear lighting, which applies the LED technology to the rear lamps in addition to the already common application to the front lighting of the vehicle. LED lamps offer a series of advantages, from style and comfort to economical and energy saving reasons.
   - *Wiper Systems*: the product group develops a wide range of technologies dedicated to the cleaning of windshields, rear windows, side windows and optical sensors, ensuring the required level of visibility for passengers and autonomous cars. AquaBlade®, as illustrated in Figure 2.5a, is an example of VIS's innovative solutions: it introduces a wiper blade with channels that distribute water through holes located along its length. This way the use of nozzles is not necessary, avoiding driver visibility obstruction by water jets when cleaning the windshield



(a) AquaBlade®　　　　　(b) LED rear lighting

Figure 2.5: Examples of Valeo VIS's automotive solutions

as well as reducing the amount of fluid necessary in the cleaning process.

5. **Valeo Service (VS)**: this division supplies both automakers with original equipment spare parts and aftermarket customers with replacement parts, providing products with Valeo standards fabricated by the other Business Groups. With a worldwide market coverage, Valeo Service provides its customers with a very wide range of automotive products and services for the aftermarket activity, ensuring quality excellence and parts availability. VS also offers a portfolio dedicated exclusively to the independent aftermarket, as the HydroConnect®(Figure 2.6a), an innovative and efficient wiper system, and the Ultrasonic Parking Sensors (Figure 2.6b), a product for which VS is the only player on the market that offers it to the aftermarket [46].

(a) HydroConnect®　　　　　(b) Ultrasonic Parking Sensors

Figure 2.6: Examples of Valeo VS's automotive solutions

2.2 Valeo Santena plant

Valeo has 4 sites in the Italian territory: in the cities of Santena, Pianezza and Mondovì, in Piedmont region, and Frosinone, in Lazio region. Figure 2.7 shows the geographical location of the four Valeo production plants in the Italian territory. Together, they generated sales of €268 million in 2016, employing more than 1,000 people [48].

Figure 2.7: Location of Valeo's manufacturing plants in Italy

Table 2.1 shows the footprint of Valeo's activities in Italy - the four production facilities and their main figures (floor surface, number of employees and sales volumes).

Table 2.1: Valeo's manufacturing plants in Italy and their main figures (data of 2015). [48]

Production plant location	**Business Groups**	**Built-up area** [m^2]	**Number of employees**	**Yearly sales** [**k€**]
Mondovì	PTS	30,000	581	140,000
Santena	CDA/VS	20,000	232	99,000
Pianezza	VIS	22,000	170	21,000
Frosinone	THS	23,800	168	8,000

The Santena site was built in the 1970s as a backup point for the Mondovì plant, responsible for the production of clutch components, and also as a multi-product line R&D center. However, in 1992, the R&D units were moved to the manufacturing sites, while the testing facilities remained in the plant [48]. It was

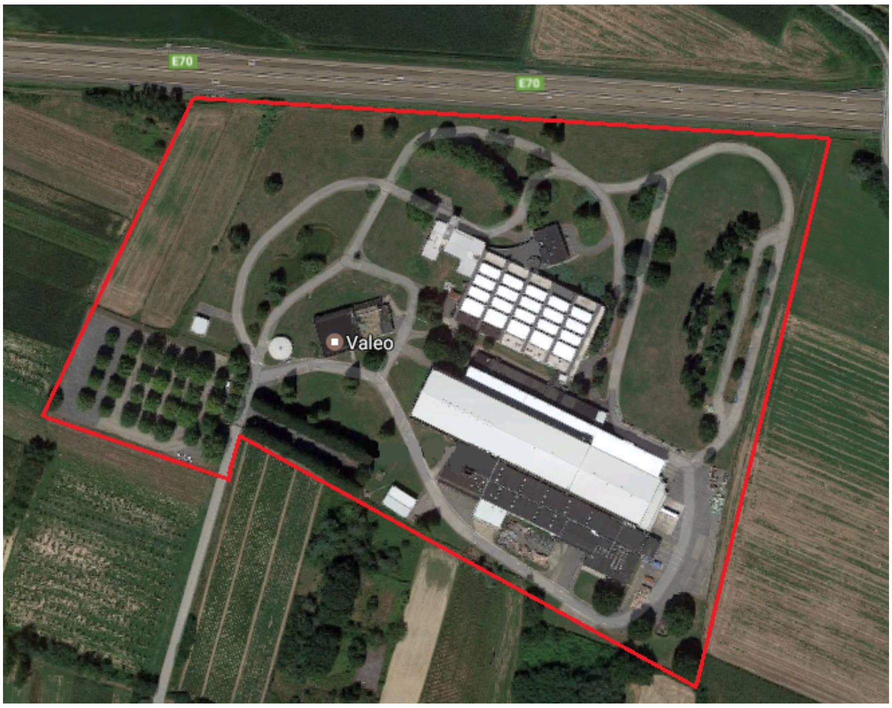


Figure 2.8: Top view of Valeo Santena plant

only in 2014 that Valeo moved its CDA's manufacturing facilities from Felizzano, also in Piedmont region, to Santena.

The site is placed in the city of Santena, in the industrial area of Turin, in Piedmont region, and comprises a 115,000 m^2 total surface and a 20,000 m^2 covered surface. A top view of the plant is shown in Figure 2.8. This is a strategic location since it is close to many important automaker plants in the region as well as to the metropolitan area of Turin, which provides the availability of a skilled workforce with qualified competences [48].

This site hosts three Valeo divisions:

- *Valeo Italy National Directorate (ND) and Shared Services*: it is the central office of Valeo's operations in Italy and it has a managerial role only. This division currently employs 40 people.
- *Valeo Service Adriatic (VSAT)*: it is responsible for the storage and distribution of spare parts for Italy, Greece and the Balkans region. Its aftermarket warehouse represents 60% of the plant's covered area, employs 90 people and generates annual sales of €70 million.
- *Valeo CDA Interior Systems Control (ISC)*: the manufacturing plant produces interior control components for the automotive premium segment. With a total of 112 employees, it represents €26.6 million in annual sales.

2.3 Valeo CDA ISC

Only the CDA ISC's manufacturing plant is the object of this thesis since it is the division in which the author developed the stage experience. Its main clients are automakers from the premium segment such as Ferrari, Maserati, Bentley, Aston Martin, Rolls Royce, and Alpine. Figure 2.9 shows that Ferrari and Maserati together represented 83% of the plant's sales in 2016 [48].

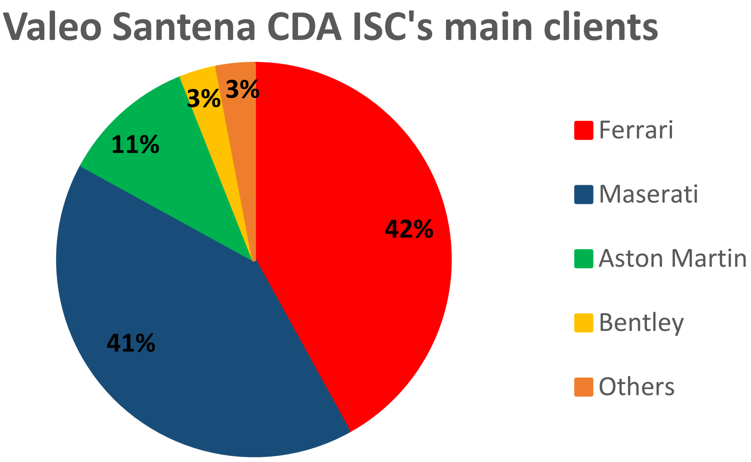


Figure 2.9: Valeo Santena's main clients by sales volumes (2016) [48]

Valeo works with a wide network of suppliers. A significant part of its components is supplied by local companies, within the Piedmont region, whose production is almost totally dedicated to the Valeo Santena plant. Additionally, the plant receives materials from all the Italian territory, supplied by companies such as Progind, Barnem, Compatech, and T.R.C. Some specific components, not available in the Italian market, are supplied by international companies, such as Howell Tomkins (United Kingdom), Faurecia (France), HDO (Germany), and WTOO (China).

In 2017, the plant's product line included around 1,700 active finished good (FG) references and more than 3,000 active component references. Valeo CDA ISC's product portfolio can be divided as follows [48]:

(1) Switches and Dome Control Modules: this set of modules utilizes switches and domes for controlling specific functions of the car such as A/C, electric windows and mirrors positioning, seats heating and trunk opening. Together they represent the largest portion of

Figure 2.10: Ferrari's A/C control by Valeo [48]

the division's sales (34% in 2016 figures). As a representative example of this product category, Figure 2.10 shows a Valeo design for an A/C control module for a Ferrari model.

(2) Top Column Modules: the module includes two levers with rotary switches, a structural frame, and a controlling system. This product is assembled and attached to the vehicle's steering wheel, as shown in Figure 2.11. The Top Column Modules provide the controlling mechanism for the outside lightening system as well as the windshield wiper movement. Representing 30% of yearly sales, this line of products is also very expressive for the company's revenues.

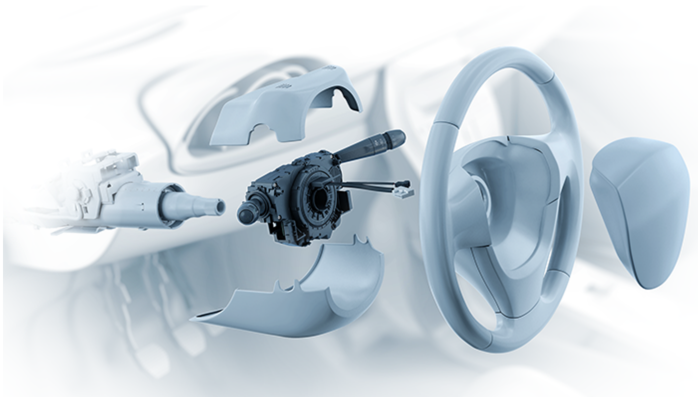


Figure 2.11: The Top Column Module by Valeo and its assembling [48]

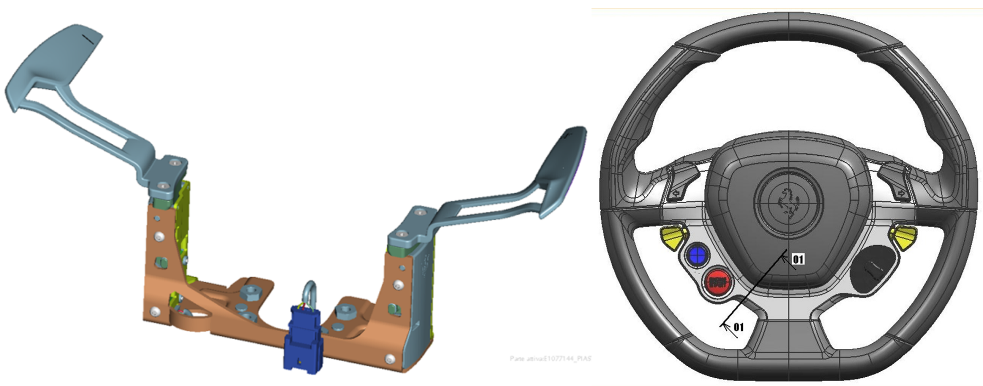
(3) Control Panels and Faceplate without Displays: representing 13% of sales, these control panels offer a series of switches and buttons that control a number of vehicle's functions. Figure 2.12 shows the Control Panel produced by Valeo for Aston Martin vehicles. It includes real glass capacitive buttons painted and laser etched, as well as rotary knobs in machined aluminum, providing A/C controlling for each of the front seat passengers, sound system control, and other vehicle's features.

Figure 2.12: Aston Martin's Control Panel without display by Valeo [48]

(4) Displays and Connected Faceplate: the product line that performed the strongest growth over the last 5 years in CDA ISC, the displays and connected faceplate provide 10% of the plant's total sales. The product consists of a traditional control panel (with its typical set of switches and rotary knobs for controlling of vehicle's internal features) and a display with touchscreen function. A representative example of this line of products is shown in Figure 2.13. It illustrates one of Maserati's control panels with integrated display designed by Valeo and produced in Santena's plant.

Figure 2.13: Maserati's Display by Valeo [48]

(5) Other products: they represent 13% of CDA ISC's sales. The gear paddle shifts, an increasing trend in the premium automotive market, represent an important portion of this category's sales. Figure 2.14a illustrates a Valeo solution for gear paddle shifting with laser etched aluminum levers for Maserati. Another important example of a product line within this category is the controlling solution integrated into the steering wheel. It consists of a group of switches that are implanted into the structural frame of the steering wheel capable of controlling vehicle's internal features. Figure 2.14b shows a Ferrari's steering wheel with integrated switches designed by Valeo.



(a) Maserati's gear paddle shifts (b) Ferrari's steering wheel

Figure 2.14: Other automotive solutions provided by CDA ISC's Santena plant [48]

Chapter 3

Current plant layout and material handling scenario

The scope of this chapter is to describe the current MHS utilized in Valeo Santena CDA ISC's manufacturing plant for the transportation of materials from workcells. Initially, the manufacturing layout is reported, evidencing the different areas of the plant and their function in the company's organizational system. The discussion is followed by a general description of the main stations employed in the production system, as well as the categories of products processed by those machines. The different packaging materials in which components and finished products are placed are also described. Finally, the current MHSs utilized by the company are specified, from the equipment employed in the task to the way it is utilized by the operators, opening a discussion about the effectiveness of this system.

3.1 Manufacturing layout

In order to understand the functioning of the current MHS employed by Valeo CDA ISC for the transportation of materials within the plant, a complete comprehension of the manufacturing layout is required to understand its requirements and constraints.

The plant layout is illustrated in Figure 3.1. This illustration divides the plant into its main parts, identifying them by colors. The plant represents a total area of about 5,450 m^2 (recall that this is related to the CDA ISC plant, which is only a subset of the area reported in Table 2.1).

Valeo CDA ISC uses a cellular manufacturing system for the assembling and production of its FGs. This type of manufacturing system is suitable for the company's characteristics, given that the plant's production volumes are low (an average weekly volume of 60 units per active FG), the number of different finished products are considerably high (around $1,700$) and they present a quite high level of similarity of production processes between different products. The manufacturing system is more deeply discussed in Section 3.3.

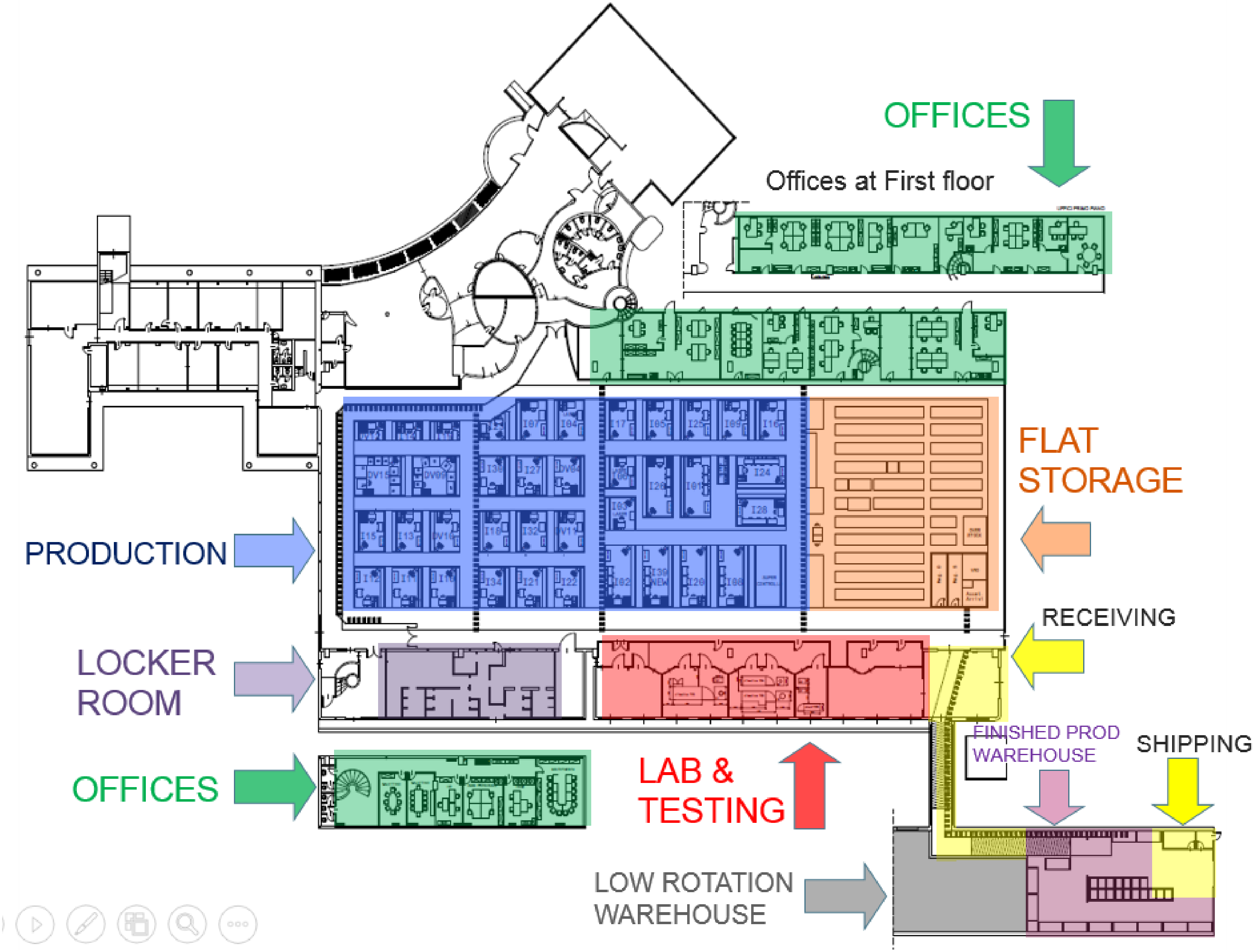


Figure 3.1: Valeo Santena CDA ISC plant layout

The production area (indicated by the blue color in Figure 3.1) is divided into 31 cells and is in the central position of the layout, representing the largest portion of the plant area (about 1,900 m^2). Figure 3.2 shows a general view of the production area of the manufacturing plant.

Figure 3.2: The production area

The locker room (purple area in Figure 3.1) is placed strategically close to the production area and the entrance room. This area is used by production operators for changing their clothes to the appropriate ones before starting working and taking them off before exiting the plant, as well as providing a bathroom area for operators to be utilized during their work pauses. The locker room occupies a surface of 240 m^2.

The offices (green area in Figure 3.1) are placed in a peripheral position, allowing for a wide view of the production area. The offices are divided into two floors: the ground floor comprises offices that have a direct contact with the production area (Logistics, Production and Quality departments), while managerial departments such as Finance, Sales, Human Resources, R&D and Company Directory are placed on the first floor. Offices occupy a total area of approximately 1,200 m^2.

The lab and testing area (red area in Figure 3.1) has a series of test benches and a wind tunnel, which is used by the Valeo Group for testing prototypes of different systems for new vehicles. The wind tunnel tests are usually performed on engine cooling systems (with a dedicated fan), A/C systems and other thermal system prototypes. The other test benches are dedicated to tests and quality checks of ISC's components and finished products, as well as prototypes of new projects. The total surface area of the lab is around 460 m^2.

The receiving area (yellow area in Figure 3.1) is placed close to the flat storage area so that to minimize the traveling distance of arriving components. An employee from the Logistics department is responsible for controlling the documentation of the arriving material, as well as the quantity received and the pack-

Figure 3.3: The shipping dock

aging type, which should be compliant with Valeo standards. The receiving area occupies a surface of 150 m^2.

The shipping area (also in yellow in Figure 3.1) is located in one of the extremities of the plant. It comprises one shipping dock, as in Figure 3.3, a picking area (space dedicated to the picking of finished products according to shipping orders), a packing area and a small office, representing a total surface area of 200 m^2.

Figure 3.4: The finished goods warehouse

The finished goods warehouse (FGWH) (light purple area in Figure 3.1) is placed strategically close to the shipping zone. This warehouse is dedicated to the stocking of FGs waiting for a picking order, and it utilizes traditional racks as the storage system, as shown in Figure 3.4. The ground floor is dedicated to pallets with finished products, while the rack's first level stores pallets with empty packaging material. The warehouse occupies an area of approximately 270 m^2.

Figure 3.5: Dedicated gravity flow racks inside a cell

The production components can be stored in four different zones in the plant:

1. **On dedicated gravity flow racks inside the cells**: in order to minimize the components traveling distance inside the plant, the ideal solution would be to store them as close as possible to the cell in which it is consumed. As previously mentioned, the physical space available does not allow for adopting this solution to all cells, but to a limited number of cells. For that reason, 9 out of the total 31 cells have gravity flow racks (Figure 3.5) inside the cell itself, reducing as much as possible the traveling distance of these materials from the racks to the machines and vice versa (if a component's packaging unit is not yet completely consumed and has to be returned to the rack for a future production batch). These selected stations are here called Type 1 cells, while cells without racks inside their assembling area are called Type 2 cells. In Type 1 cells, the operator (or eventually more than one operator) is responsible for picking all the required components from the racks. The process of choosing these cells was based on their production volume, giving the priority for the cells with a higher number of parts produced per unit of time. This selection criterion, although important for the comprehension of the production area layout, is not the scope of this thesis and will not be discussed in detail. It is also important to highlight that gravity flow racks are suitable for a 'first-in-first-out' (FIFO) consumption policy, i.e. when a material is required by the production cell the packaging unit that should be consumed is the oldest one in the warehouse. This policy is required for this kind of production environment because some materials employed in the production, due to their chemical configuration, have to be consumed in a small time window (usually a few weeks). Therefore it is essential to track

and respect the FIFO consumption policy. Gravity flow racks help operators to identify quickly the oldest packaging unit: the standard procedure requires that the rack is always fed from its rear part, and the material to be consumed is taken from the rack's frontal part. This way, it assures that the oldest batches are firstly consumed.

2. **On the flat storage area**: this area (in orange in Figure 3.1) is dedicated to the storage of components utilized by Type 2 cells and is adjacent to the production area, facilitating the flow of materials. The flat storage area, as shown in Figure 3.6, stores components of medium-to-high rotation, as it will be subsequently discussed in Section 3.2. The materials, named common components, are stored mainly in gravity flow racks, divided into eight rows. Components with bulky unit loads or high weekly consumption volumes are exceptionally placed in roller boards, as in Figure 3.7, so that to better utilize the available space. The flat storage area occupies a total surface of 650 m^2. We use in this thesis the convention adopted by Valeo, which considers as flat storage both roller and gravity flow racks.

Figure 3.6: The flat storage area

3. **On the "common components" racks**: some of the company's components are consumed by more than one cell, representing about 5% of the totality. These materials are stored in a row of four gravity flow racks in the flat storage area, in its closest portion to the production cells.

(a) The roller board

(b) High volume-based consumption rate component stored on a roller board

Figure 3.7: The use of roller boards as storage system in the flat storage area

4. **On the low rotation warehouse**: the low rotation warehouse (grey area), denominated NMAG, is responsible for the storage of components of low rotation, as it will be discussed in Section 3.2. Traditional racks are used as the storage system in this warehouse, as shown in Figure 3.8, representing a total area of 380 m^2. From the layout (Figure 3.1), it is clear that this area is quite far from the production zone, for that reason the warehouse is dedicated only for the storing of the least frequently used components in the plant.

Figure 3.8: The low-rotation components warehouse

Additionally to the previously stated options for components storing, there is a dedicated area for components in overstock, i.e. components received from the suppliers in quantities larger than the volume capacity of its storage location. In this case, the portion of the material to be stocked that does not fit its dedicated storing area is positioned in the overstock zone, which is located in the flat storage area.

The type of manufacturing layout can be approximated by a U-shaped layout. This can be seen in Figure 3.9, which indicates the flow of materials for the production of a typical finished product. The one represented in the figure is produced in a Type 2 cell. In this case, its components pass through the receiving area (point 1) and are stored in their specific stocking location at the flat storage area (point 2). Once there is a production order for that specific reference, its components are transported to its production cell (point 3). When the components are assembled, the FG is transported to the finished product warehouse (point 4). It then waits for its shipping order, after which it goes to the shipping area (point 5). A Type 2 cell is here illustrated as a representative example because the path through which its components travel is the more complex one (follows more steps) if compared to other cell types.

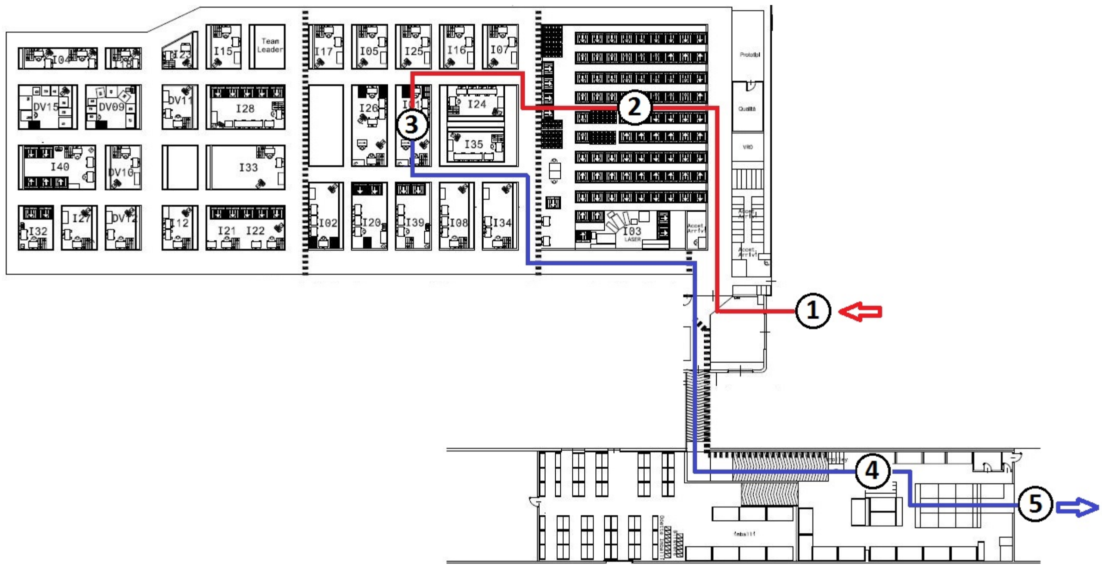


Figure 3.9: Material flow representation for a typical finished product

3.2 Components storage location

The company adopts an internal classification method for its components in order to decide in which zone of the plant layout each one of them should be stored. The reason why this classification is required is that not all components can be stored physically close to the cell in which it is utilized, because of space limitations.

The components classification is based on two parameters: its frequency of use and the average quantity requested by the production in an 18-week time horizon. Those two data are extracted from the Master Production Schedule (MPS) - which determines the number of units of a FG that should be produced in each week - and the Bill of Materials (BOM) for each finished product - i.e. the list of all the components and their respective quantity required for producing a unit of the specific finished product. This way, by transforming the demand of finished products (determined by the MPS) into the components requirements (multiplying by the quantities per unit produced given by the BOM), it is possible to specify the number of units of each component required by the production in each week.

A ranking index is attributed to each component by considering the previously cited parameters. Considering that the company employs c components in its production, let $q_{i,N}$ be the required quantity of a component $i = 1, 2, \cdots, c$ in week $N = 1, 2, \cdots, 18$ of the MPS. The average amount required by the MPS for component i in the 18-week time horizon is

$$\bar{q}_i = \frac{\sum_{N=1}^{18} q_{i,N}}{18}. \tag{3.1}$$

Let $f_{i,N}$ a binary coefficient that assumes value 1 if there is any request for component i in week N of the MPS, otherwise, it receives value 0. Analogously to (3.1), a frequency-related parameter for component i is defined as

$$\bar{f}_i = \frac{\sum_{N=1}^{18} f_{i,N}}{18}.$$

The ranking index r_i for component i is defined as

$$r_i = c(\gamma \frac{\bar{q}_i}{\sum_{j=1}^{c} \bar{q}_j} + \delta \frac{\bar{f}_i}{\sum_{j=1}^{c} \bar{f}_j}),$$

where $\gamma, \delta \in [0, 1]$ are fixed weighting coefficients. Note that the ranking index takes into account both the frequency of use and the average demand of the components.

The components are classified into four groups, namely A, B, $SLOW$, and OBS. All components with $r_i = 0$ are classified as OBS. By not considering these components, the remaining ones are listed in a descending order of r_i. The top 20% components are classified as class A, the following 60% class B, and the remaining 20% class $SLOW$. The ranking index is internally named by Valeo as “rotation” of the component. $SLOW$, thus, stands for “slow rotation”, while OBS stands for “obsolete”. Note that OBS classification does not imply that a component is in fact obsolete. The request for the component may be scheduled to a date outside the time horizon considered by the MPS.

The storage location of a component in Valeo Santena's plant is defined according to two classifications: the component's rotation (*A*, *B*, *SLOW* and *OBS* classes) and the type of the cell in which the component is utilized (Type 1, Type 2 or multiple, in case the component is used in more than one cell). Figure 3.10 illustrates a flowchart of this decision process. *SLOW* and *OBS* rotation class components are stored in the low rotation warehouse (NMAG), which is distant from the production area since their frequency of use and number of pieces utilized are very low. For components within *A* and *B* classes, the storage area depends on the cells by which the component is consumed. If it is a Type 1 cell, the component is stored directly inside the cell area. If the cell is a Type 2 one, the material is stocked on the flat storage area. In case the component is consumed by more than one cell, it is kept in a dedicated area for common components (common gravity racks).

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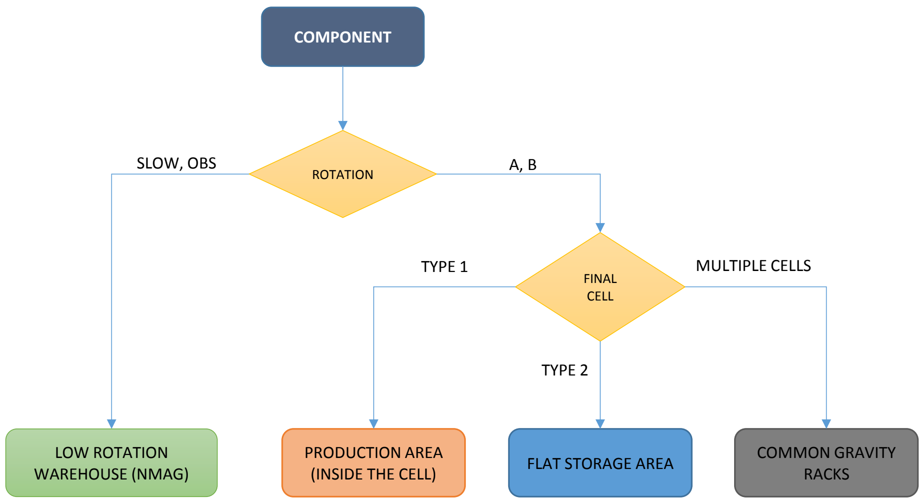


Figure 3.10: Flowchart of the component storage location decision process according to its rotation class and the type of cell in which the it is consumed

3.3 The manufacturing system

This Valeo plant utilizes a cellular manufacturing system for the production of its FGs. This system is suitable for the characteristics of the plant's portfolio due to the following reasons:

- **Relatively low production volumes**: as mentioned in Section 2.3, Valeo CDA ISC provides automotive components for the premium segment. In this selective market, production volumes are much lower compared to mass-market vehicles. Ferrari, the plant's main client, has had a yearly production volume of around $8,000$ units in 2016 [49], which is much lower than the yearly production volume of Fiat (around 4.6 million units in 2016 [50]), illustrated here as an example of a mass-market automaker.
- **Relatively high number of different products**: the premium automotive segment not only works with low production volumes but also provides

to its clients a wide range of choices in many of its vehicle's features. The internal part of the vehicles is often one of the most customized parts of the car. Differences in shapes, colors, materials, and textures in Valeo's interior controls have to be offered to these clients. The large variety of custom configurations strongly increases the complexity of material management, production planning, and forecast. A component supplied by the plant for a typical premium automaker's vehicle, with an average annual production volume of 1,000 units (which is already a low value in the automotive market), may have up to ten different configurations, each one of them with a different annual volume. For that reason, the company currently works with about 1,700 active FG references, which is a very high number for a typical automotive supplier.

- **Existence of similarities between FGs**: the wide range of component variations mentioned in the previous item provide a family of similar products with a small variation between them. That is, the production processes are very similar and it is not uncommon that the machines do not even need to be reset while changing the production from one FG to another. Also, the manufacturing processes of products for different clients may be quite similar. Due to these similarities, the products can be divided into families of similar production processes.

- **Constant production variations**: another important characteristic of the premium automotive segment is the constant need for innovation. This market seeks for the most technological, state-of-the-art cars and their features, so automakers usually launch new vehicles and innovative solutions more frequently than other automotive market segments. To Valeo, this means that new projects are launched frequently, even if the changes between two subsequent versions of a vehicle may not be so significant in terms of Valeo's components. The consequence of this market characteristic is that Valeo's portfolio constantly changes, and so the production volumes and even the production layout may vary in time. That aspect of the business requires a production system capable of quickly adapting to changes in volumes and physical configuration.

Because of Valeo CDA ISC's portfolio characteristics (it can be divided into families of products that go through similar processes during production, each of them with relatively low annual production volumes), a cellular manufacturing system may be the one that most suits its production characteristics. This way, each cell is dedicated to producing a family of similar products, each one of them with a low production volume. The production characteristics implicate on constant changes in the part to be produced, and because of having similar products the set-up time is reduced or even null. It is quite common that, in an 8-hour shift, a cell may produce up to ten different product references.

This Valeo plant is mainly an assembly production site. The production processes are only assembling procedures, many of them performed manually by an operator with the help of mechanical devices. For this reason, the plant's level of risk (for injuries, fire, electrical incidents) is very low.

The only exception is cell I03, as it will be better described in details in Table 3.1. This cell consists of two laser machines and a washing station. The machines are used to laser-print symbols into plastic, metallic, or glass-made materials, changing its chemical and mechanical compositions (it is then a manufacturing process). The washing machine is used to polish glasses after the laser procedures.

The plastic parts, before going through the laser process in cell I03, receive a thin varnish coating (this procedure is performed by a supplier). The varnish has its color changed when the laser is applied to its surface, making it possible to see the desired symbol. Figure 3.11 shows a plastic part with varnish coat before and after the laser process performed in this cell. A part of the post-laser plastic parts still has to be resent to the supplier in order to receive a second coating for the protection of its visible surface (this is very common when dealing with delicate, aesthetic components).

Figure 3.11: Plastic part with varnish coat before (on the left) and after (right) the laser process

The glass-made parts, on the other hand, receive a different type of coating, but with the same principle: a varnish is applied so that, once it goes through the laser process, it reacts and changes its color. The glass goes then through the washing station for polishing, and it is then ready for the assembling process.

This cell is an intermediary station, that is, it does not produce FGs, only semi-finished parts. The output of the station is either transported to a supplier for its final coating or goes to another cell in which it will be consumed for the assembling of finished products.

A simplified version of the plant layout is shown in Figure 3.12. As previously mentioned, the production area is divided into 31 manufacturing cells, which are indicated as 'DV' or 'I', followed by the number of the cell. The designation 'DV' is given to cells dedicated to the production of top column modules (DV stands for '*devioguida*', the Italian word for column switch), while the 'I' one is given to cells dedicated to the other products of the plant's portfolio (I stands for '*interruttore*', i.e. switch).

Table 3.1 indicates the families of products made by each manufacturing cell, the storage location of its components (whether the cell is Type 1 or 2, i.e. with or without dedicated racks inside the cell area) and the average number of units produced by each cell on a weekly basis.

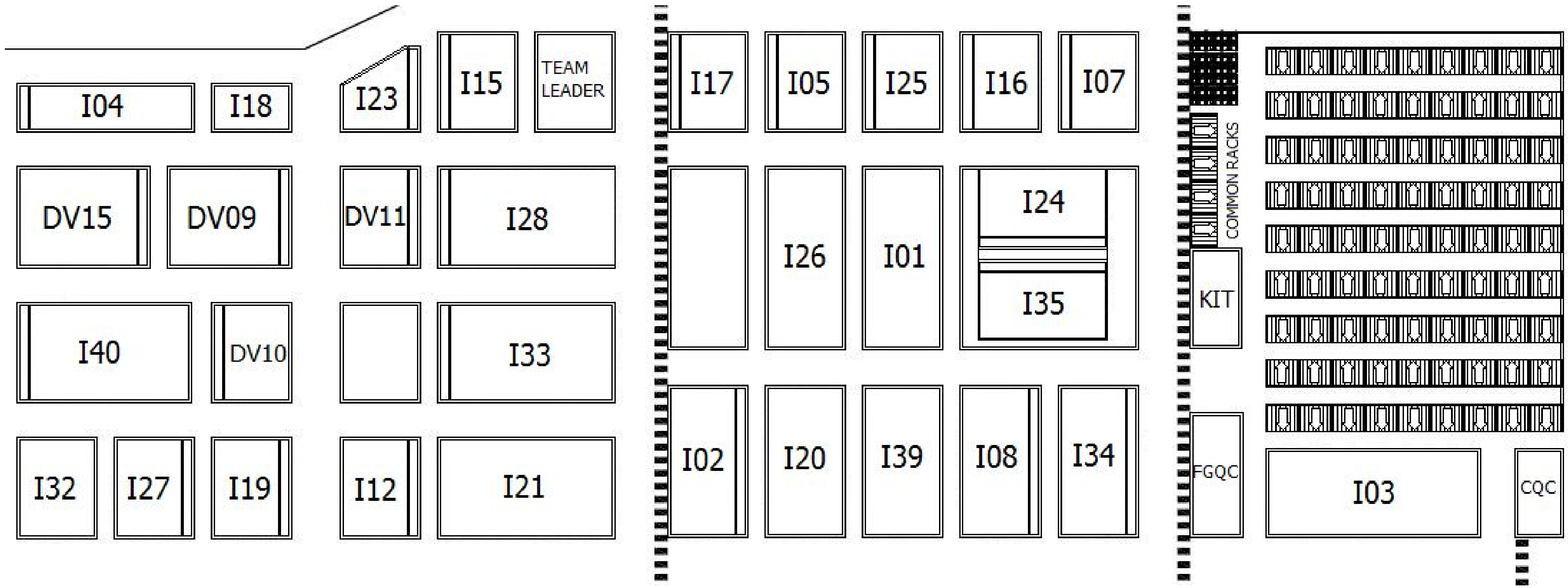


Figure 3.12: Layout of the production area

Table 3.1: List of the site's cells and correspondent products categories, cell type (related to the components storing location) and average weekly production volume

Cell	**Products**	**Cell type**	**Average weekly production volume (units)**
DV09	Final assembly of top column modules for Maserati	2	235
DV10	Assembly of top column modules' subgroups to be assembled in DV09	2	235
DV11	Quality check and packing of top column modules from DV09	2	149
DV15	Top column modules for Fiat Chrysler Automobiles (FCA)	2	223
I01	External lighting and sound system command	2	430
I02	Gear shift paddle for Ferrari	2	72
I03	Laser station for plastic and glass aesthetic parts (supplies multiple cells)	1	9587
I04	Sound system control with rotary knobs for Ferrari	2	74
I05	Wing mirror and seat positioning commands for Ferrari and Bentley	2	1303
I07	Simple buttons (Bluetooth®, parking cameras, trunk opening, door locking and unlocking) for Ferrari and Maserati	2	359
I08	Steering wheel switches for Ferrari	2	237
I12	Windows command for Maserati	2	197
I15	General interior control switches for multiple clients	2	298
I16	Parking, engine start and external camera switches for Ferrari	2	1035
I17	General interior control switches for Maserati	2	737
I18	Windows positioning and seat heating commands for Maserati	1	447
I19	Windows positioning, trunk, back window and retractable roof opening commands for Ferrari	2	1878

Table 3.1 - continued from the previous page

Cell	Products	Cell type	Average weekly production volume (units)
I20	Gear shift paddle for Maserati	1	916
I21	Interior devices commands with capacitive glass buttons for Aston Martin	1	23
I23	Electronic control unit (ECU) for Ferrari and Aston Martin	2	371
I24	Heating, ventilation, and air-conditioning (HVAC) commands and display with connected faceplate for Ferrari and Maserati	2	497
I25	General interior control switches for multiple clients	2	249
I26	Parking brake and other actuators command for Ferrari	2	12
I27	Wing mirror and window positioning commands for Maserati	2	1038
I28	General interior control switches (park sensor activation, trunk opening, emergency light) and seats predefined configuration command for Ferrari	1	353
I32	Interior control commands with two rotary knobs for Maserati	1	1286
I33	HVAC commands and general open/close switches faceplate for Ferrari and Maserati	1	1179
I34	Seats predefined configuration command for Maserati	2	2501
I35	Display with connected faceplate for Renault Alpine	2	5
I39	Gear shift paddle for Maserati and Aston Martin	1	299
I40	Steering wheel support with switches, engine start/stop switch and automatic gear selection command - rear, neutral, drive (RND) - for Renault Alpine, Aston Martin and Rolls Royce	1	246

There are important comments to be made about the information provided by Table 3.1:

- I24 and I35 are special cells and differ from the others in their physical configuration. While all the other cells perimeters are defined only by white stripes on the floor, without any physical boundaries, these two specific cells were built inside an enclosed room (both cells are placed in the same room). This configuration had to be adopted due to characteristics of the FGs that are produced in those cells (mainly fragile, touch-sensitive displays and integrated electronic circuits). In this room, air temperature and humidity are constantly controlled, as well as its dust concentration level. The room is completely isolated from the external environment, because of its two-door entrance procedure - one door faces the external environment while the other one faces the internal part of the room, and they cannot be opened simultaneously. In addition to the traditional protective clothing (rigid, isolating shoes, gloves and industrial coat with electric protection), operators are also obliged to use an industrial hat. Carton boxes are not allowed in the room, so plastic boxes are required for both components and finished products.

- From Table 3.1, it may seem that I35 cell has a very low weekly production volume. This is explained by the fact that it is dedicated to one of the company's new project. In the following months, the production volumes are expected to increase.

- The same observation may be made about I21 cell. In this case, the cell's production lead time is large compared to other products due to its complexity and the required level of quality checks. Even if the cell was not working in its full capacity, this partially explains the low production volume.

- I26 cell once again presents extremely low production volumes, but in this case, this cell is about to be excluded from the plant layout (its products are passing through a phase-out process), leaving space for a new manufacturing cell. This enforces the idea that the production system is constantly changing, so system flexibility is very important.

- As the previous cell example, there are some cells that explore only a small portion of its production capacity. It is important to notice that Valeo, as an automotive supplier, is obliged by contract to provide components for automakers throughout the whole life cycle of the vehicle in which its products are assembled. That means that, even once the production of the final vehicle is permanently stopped, Valeo still needs to ensure the capacity of providing a predefined number of units of each component it supplies, or to retain the machines required for their production for a predefined period of time. The effect of these contractual agreements is that cells that assemble mainly obsolete products cannot be permanently excluded while the phase-out contract is still valid, and consequently, they are used less frequently (sometimes only a few hours in a week).

In addition to the cells described in Table 3.1, there are other areas on the production area layout (Figure 3.12) to be cited:

- **Components quality control (CQC) station**: this station, located close to the receiving area, is responsible for making quality control checks to specific, critical components. Only a small portion of the receiving components goes through the quality check. The selected components may be prototypes or in final stages of new projects (pre-mass production phase), or even recently modified components. Nevertheless, some critical components (due to their economic value or high-quality requirements) may be continuously checked even after a long period from the start of production.

- **Finished goods quality control (FGQC) station**: analogously to the previous item, this station performs quality checks in FGs. Many of the cells have a set of sensors to assess quality specifications, but, due to machine limitations, further quality control may be required. Projects in early stages also use this station to perform quality analysis and possibly detect design problems.

- **Production team leaders station**: this area is dedicated to the production team leaders, responsible for supervising and supporting the production. In this station, team leaders have access to the information system and the production schedule.

- **Common components racks**: as previously cited in Section 3.2, components that serve more than one cell are stored in dedicated racks close to the production area.

- **Kit preparing area**: in Type 2 cells, when a FG is requested, the components to be assembled (stored in the flat storage area) have to be picked, sorted, and delivered to the cell. In the kitting area, an operator from the Logistic department is responsible for printing the FG's BOM, in which the required quantity of each component is displayed, as well as its storage location. The operator then picks up the components (in quantities equal or larger than the requested ones), positions them on a cart (forming the so-called kit) and places it inside the workcell in which they will be consumed.

3.4 Typical cell description

Workcell I28 (a Type 1 cell) is used in this section to represent the configuration of a typical cell in the plant. This workcell is chosen to represent the typical cell layout because it has all the possible elements a cell in the plant can have (e.g. workstations, gravity racks, different work positions, etc.). Other cells may either have all the elements present in cell I028 or just a portion of them. Figure 3.13 illustrates its layout, while Figure 3.14 shows a picture of the cell.

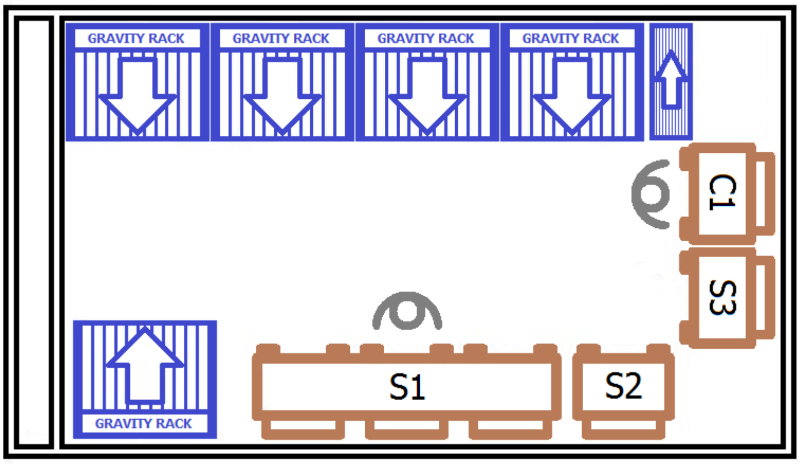


Figure 3.13: Layout of a typical Type 1 cell

The main elements of the layout are:

- Gravity flow racks, in which the components exclusively consumed by this cell are stored.
- Assembling stations *S1*, *S2*, and *S3*, including assembling tools, supports for components, emergency button and a monitor that displays the sequence of operations to be performed.
- Control station *C1*, responsible for verifying assembling correctness by means of a series of sensors. A monitor displays the sequence of operations for the verification and the results of the analysis.
- Gravity flow exit point, on which FGs full packages are placed to be picked up and transported to the FGWH.

Two operators are illustrated in Figure 3.13, each of them responsible for executing a portion of the assembling and controlling processes. It is important to note though that the major part of the workcells is designed to be operated by a single person.

The different flows of materials inside a typical cell are illustrated in Figure 3.15. The components (indicated by the red color) come from the receiving area and are stored in the gravity flow racks. When requested, they are picked and

Figure 3.14: A typical workcell - including three assembling stations (at the right), a control station (at the back) and gravity flow racks (at the left)

sourced by an operator and enters station *S1*, when the assembling process starts. Components then become work-in-progress materials (blue color), passing through stations *S1*, *S2*, and *S3*, after which they become a FG (green color). It is then controlled in station *C1*, packed and placed on the exit point to be collected and transferred to the FGWH.

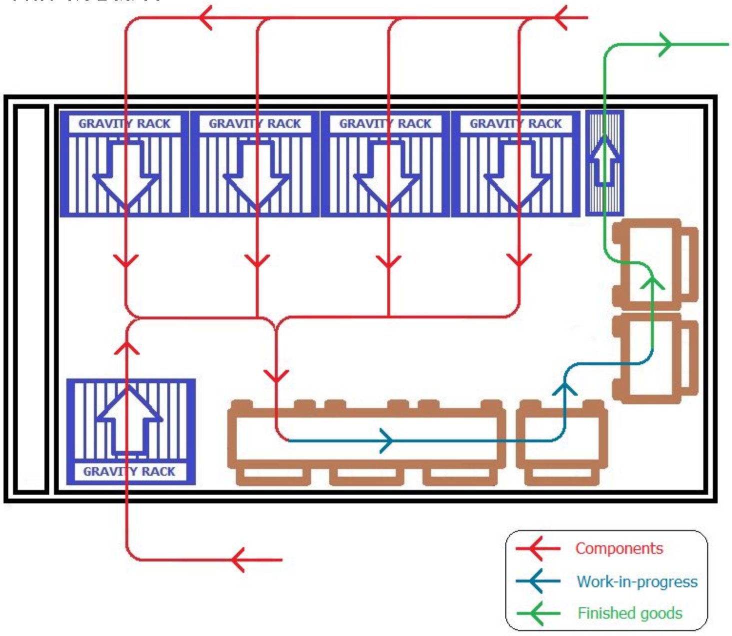


Figure 3.15: Flow of material in a typical cell; from components (on racks) to work-in-progress and FGs

The average cell (i.e. a cell whose characteristics are defined by the average value of all workcells) has a surface area of about 10 m^2, a weekly production volume of 563 units, corresponding to 6 different products.

3.5 Description of the material handling system for the output material flow from workcells

The focus of this section is to analyze the different material handling equipment utilized by Valeo for the transportation of material from workcells. There are 5 possible kinds of material flow from the cells:

(a) FGs to be transported to the FGWH: those items are completely assembled, checked and packed, therefore ready to be stored and later shipped to the final client.

(b) FGs to be checked at the FGQC station: these goods are transported from the cell to the quality check station, where they are analyzed and afterward transported to the FGWH.

(c) Semi-finished goods (SFGs) to be transported to another cell (inter-cell flow): parts that have gone through a manufacturing process in a specific cell, but are not yet completely assembled into a finished product, going through other processes in another cell. In practice, this case applies to part of the output of the laser cell I03 for specific SFG that are consumed by cells I20 and I39.

(d) SFGs to be transported to the shipping area in order to receive an intermediary manufacturing process by a supplier: parts that are worked internally but have to go through further processes performed by an external supplier. This is the case of a portion of I03 cell's production output.

(e) Components empty packaging material: components utilized by cells arrive from suppliers in two possible types of packaging material, plastic Odette-standard boxes (reusable) or carton boxes. This will be subsequently discussed with more details in Section 4.2. After the complete consumption of a package, carton boxes are disposed, but plastic boxes have to be moved to a specific area close to the shipping dock, in order to be sent back to the supplier.

The transportation of finished products from the workcells to the FGWH is performed by means of two different material handling equipment:

- **A towing truck**: it is operated by a stand-on operator. The truck is manufactured by Toyota, a TSE150-708 model, illustrated in Figure 3.16. Appendix A.1 shows the technical specification and main characteristics of this model. A series of wagons are attached to the train and towed by it. The operator is responsible for picking up packages containing finished products as the output of the different workcells, performing a labeling verification and placing them on one of the wagons attached to it. The packages are then transported to the FGWH, at which the operator is responsible for leaving the filled wagons to be taken care by warehouse operators, and reattaching new empty wagons to the towing train.

Figure 3.16: The towing truck model TSE150-708 manufactured by Toyota [51]

Figure 3.17: Hand pallet truck model LHM230 manufactured by BT [52]

- **A hand pallet truck (pallet jack)**: it is handled manually by the operator, which applies force on the lever to guide it and control the vertical movement of the forks. It is used exclusively for handling materials placed on pallets. The hand pallet truck utilized by Valeo is manufactured by BT (a Toyota Material Handling Group's brand), model LHM230, illustrated in Figure 3.17. Appendix A.2 shows the technical specification and main characteristics of this model. The procedure followed by the operator is similar to the previously described one, from the labeling check to the transportation to the warehouse.

The choice of the proper material handling equipment for the transportation of SFGs and FGs from cells depends on the packaging material of the transported good. This will be subsequently explained in Section 4.2.

By considering exclusively the activities performed with the use of the towing truck as material handling equipment, the work of the operators was observed in order to evaluate the performance of this transporting system. Initially, the number of routes performed each day and the route duration were measured during five days of work. We here consider a route duration as the time interval between the instant the operator leaves the drop-off point (in the FGWH) and when he comes back to the same initial point. In the meantime, the operator drives until the various cells, picks up boxes from the different cells and bring them to the initial point, at which the filled wagons are left and replaced by empty ones. By considering the observed data from the real operation, we evaluated that the towing truck's operators perform, on average, 34 routes a day with a duration of 15.7 minutes. We conclude that the average total time spent by Valeo's operators on the studied material handling activities is 533.8 minutes.

Chapter 4

Optimization of the current material handling system

In the previous chapter, the current MHS employed by Valeo to transport materials from cells is described in details, reporting the basic functioning of the system. The initial perception of the system's performance is that it provides a good service level, i.e. it seems that the average total queued volumes in cells that wait to be transported to the warehouse is quite low. This perception will be subsequently measured into analyzable data in Section 6.1. On the other hand, by observing the boxes that arrive on the FGWH, the wagons are usually not fully loaded, i.e. usually when the towing truck operator finishes a route, there is still a significant portion of the wagon's capacity that has not been used. This motivated us to imagine that the operators are performing more routes than necessary, considering that the wagons capacity is not fully utilized. Therefore, it is expected that a labor cost reduction could be achieved by planning in a more organized way the frequency at which the operators perform picking-up routes. Once again, this perception will be translated into data in Section 6.1.

The objective of this section is to analyze the volumes to be transported by the towing truck in such a way that its routes around the plant for picking up boxes can be rationalized in a planned way, avoiding unnecessary displacements and exploiting as much as possible the wagons transporting capacity. The goal is to implement a cost reduction strategy with considerable results from the economic viewpoint, while not requiring any initial investment nor significant changes on the current working operation.

4.1 Scope of the optimization process

Although there are many material handling activities performed in the considered plant, the scope of this thesis is to evaluate ways to improve the execution of two of those activities:

- transportation of finished products from cells to the FGWH;
- transportation of work-in-progress materials between cells;
- transportation of components empty plastic boxes after their use in a cell to a specific deposit area close to the shipping area.

4.2 Packaging materials employed by the production system

In order to evaluate the dimensional requirements of the towing truck system in terms of capacity, it is important to analyze the different types of packaging materials used for storing SFGs and FGs.

Valeo employs fourteen different packages for its FGs in the Santena plant. There are two main categories: Valeo's carton boxes or clients' plastic returnable boxes. Carton boxes can be used to pack products to any of the clients, usually employed for phase-out products. Plastic boxes, on the other hand, are property of the client and are specific to each of them. These boxes undertake a cyclic system: the packages are filled with products, sent to the client, which consumes the products and returns the empty boxes to Valeo so that they are used again in the next cycle. The boxes may differ in dimension, color, gripping characteristic, and weight.

Figures 4.1, 4.2, 4.3, 4.4, and 4.5 show the different packaging materials dedicated to FGs.

(a) 3147　　(b) 4280　　(c) 6280

Figure 4.1: Different types of packaging material utilized for FGs - part 1

(a) 4203 (b) BFDA4285 (c) AML2406

Figure 4.2: Different types of packaging material utilized for FGs - part 2

(a) AML2405 (b) B4147 (c) B6280

Figure 4.3: Different types of packaging material utilized for FGs - part 3

(a) 210 (b) 209 (c) 0018

Figure 4.4: Different types of packaging material utilized for FGs - part 4

(a) 419 (b) 50

Figure 4.5: Different types of packaging material utilized for FGs - part 5

Table 4.1 shows the main characteristics of the packages shown in Figures 4.1, 4.2, 4.3, 4.4, and 4.5. For each of them, Valeo denominates the packaging material with an internal code, reported in the first column of the table. External and internal dimensions, the material and the final client are also reported in Table 4.1.

Table 4.1: Packaging material dedicated to FGs (dimensions are provided in mm)

Valeo code	Material	External dimensions	Internal dimensions	Client
3147	Plastic	300x200x147	243x161x129	Ferrari/Maserati
4280	Plastic	400x300x280	345x262x260	Ferrari/Maserati
6280	Plastic	600x400x280	543x347x260	Ferrari/Maserati
4203	Plastic	1000x800x750	980x780x730	Maserati
B4147	Plastic	400x300x147	345x265x130	Bentley
B6280	Plastic	600x400x280	540x360x260	Bentley
AML2406	Plastic	400x300x120	370x265x115	Aston Martin
AML2405	Plastic	600x400x280	570x365x270	Aston Martin
BFDA4285	Plastic	600x400x200	570x365x195	Renault Alpine
210	Carton	300x200x120	290x190x110	Multiple
209	Carton	400x300x220	390x290x210	Multiple
0018	Carton	600x400x220	590x390x210	Multiple
419	Carton	1200x800x460	1180x780x440	Multiple
50	Carton	1200x800x750	1180x780x730	Multiple

Figure 4.6 shows the different types of packaging material dedicated to components and SFGs. These are Valeo's property, made of plastic material and identified by the green color. They are exclusively used for internal movements and transport between Valeo and its suppliers.

(a) V35 (b) V36 (c) V37

Figure 4.6: Different types of packaging material utilized for components and SFGs

Table 4.2 reports the main characteristics of the packaging material dedicated to SFGs, illustrated Figure 4.6.

Table 4.2: Packaging material dedicated to SFGs (dimensions are provided in mm)

Valeo code	**Material**	**External dimensions**	**Internal dimensions**
V35	Plastic	300x200x120	270x170x115
V36	Plastic	400x300x220	370x265x215
V37	Plastic	600x400x220	570x365x315

Since it may be difficult to analyze the output flow of packages from cells considering 17 different types of packaging material, we divided them into categories of similar packages. Since the critical factor to define the capacity of the wagons towed by the truck is the room space available to deposit the products, the parameters on which the division into categories is based are the external dimensions of the packages. We propose a classification into 5 categories as defined in Table 4.3.

Table 4.3: Definition of the 5 different packaging material categories

Category	**External dimensions (mm)**
A	300x200x150
B	400x300x300
C	600x400x300
D	1200x800x750
E	400x300x150

Given the 5 defined categories, it is possible to note that boxes from categories B, C, D, and E can be decomposed as a set of category A boxes, in terms of volumes. This can be observed in Figures 4.7 and 4.8, which illustrate the decomposition process. The relation between volumes of each category is given by

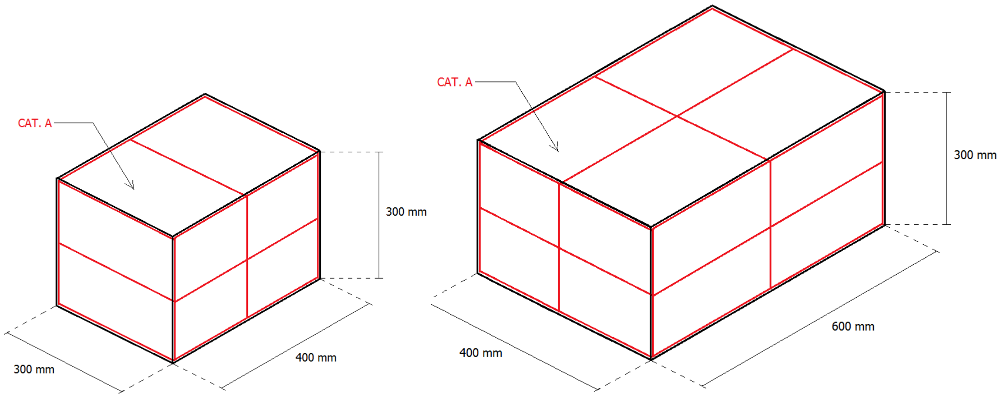
$$V_B = 4V_A,$$

$$V_C = 8V_A,$$

$$V_D = 80V_A,$$

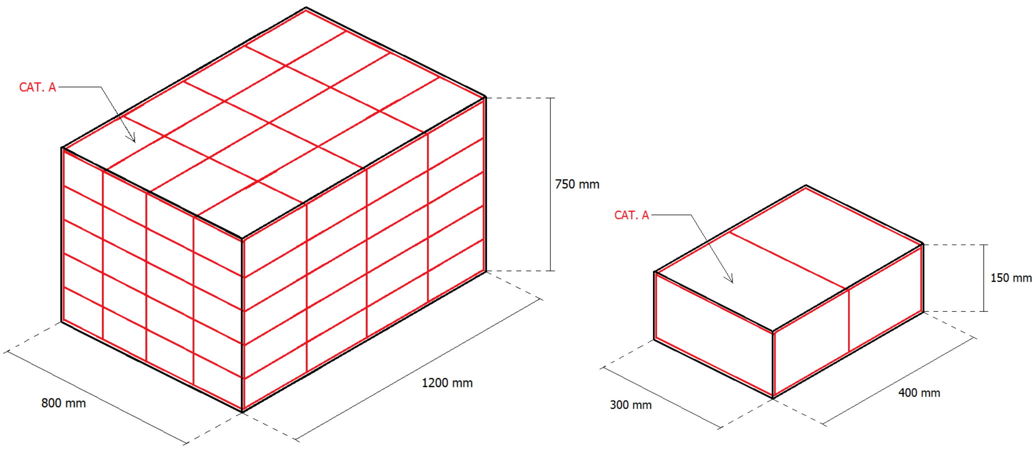
$$V_E = 2V_A,$$

where V_A, V_B, V_C, V_D, V_E are the volume of categories A, B, C, D, and E boxes, respectively.



(a) Category B (b) Category C

Figure 4.7: Categories B and C, and how they can be decomposed in terms of category A boxes



(a) Category D (b) Category E

Figure 4.8: Categories D and E, and how they can be decomposed in terms of category A boxes

4.3 Analysis of volumes to be transported from workcells

For each SFG and FG to be transported from cells, a set of data was collected from the information system of the company. For each product i, the information collected included:

- the type of packaging material associated to it (and, consequently, the package category, as defined in Section 4.2);
- the number of units per package, u_i;
- the average number of units produced per week, $\bar{q}_{w,i}$, calculated over 8 consecutive weeks.

The average production volume per day for each reference code, $\bar{q}_{d,i}$, considering that the plant works 5 days a week, can be calculated as:

$$\bar{q}_{d,i} = \frac{\bar{q}_{w,i}}{5}.$$

The average number of packages of the reference code, $\bar{p}_{d,i}$, can be then calculated as

$$\bar{p}_{d,i} = \frac{\bar{q}_{d,i}}{u_i}.$$

Once this parameter is calculated for each product, they are grouped by the cells in which they are produced. They are then subsequently sorted by the category of the packaging material, and $p_{d,i}$ are then summed up. The result of this process is shown in Table 4.4.

Table 4.4: Average number of packages (for each packaging category) to be transported from the workcells on a daily basis, considering FGs and SFGs

Cell	Cat.A	Cat.B	Cat.C	Cat.D	Cat.E
DV09	0	0	0	0.99	0
DV11	0	0	0	0.66	0
DV15	0	0	0	0.55	0
I01	0.46	2.42	0	0	2.19
I02	0	0	2.55	0	0
I03	30.33	0	5.30	0	0
I04	0	0.50	0	0	0
I05	3.23	0.40	1.10	0	0.56
I07	5.38	0	0	0	0
I08	0	0	7.62	0	0
I12	0	0.13	0	0	0

Table 4.4 - continued from the previous page

Cell	Cat.A	Cat.B	Cat.C	Cat.D	Cat.E
I15	0	0.95	0	0	0
I16	2.47	2.56	0	0	0
I17	0	4.91	0	0	0
I18	0.98	0	0	0	0
I19	5.30	3.38	0	0	0
I20	0	0	0	5.74	0
I21	0.30	0.41	0	0	0
I23	0	1.40	2.59	0	0
I24	0	4.90	0	0	0
I25	1.81	0.60	0	0	0
I26	0	0	1.24	0	0
I27	0	6.49	0	0	0
I28	1.55	1.12	0	0	0
I32	0	10.72	0	0	0
I33	1.18	5.40	0	0	0
I34	0	14.86	0	0	0.92
I35	0	0.09	0	0	0
I39	0	0	8.99	0	0
I40	0	0	2.79	0	0

4.4 Wagon layout optimization

The wagon currently used as part of the towing truck system for the transportation of goods from cells is illustrated in Figure 4.9. The wagon includes 4 wheels, 2 or 3 shelves and a hooking mechanism that allows it to be towed by a truck. It is designed to provide a vertical adjustment of the height of its shelves. A shelf can be fixed in 19 different height positions, with a step $p = 5$cm between them.

The dimensional parameters of the wagon are reported in Table 4.5. The total internal space available for placing materials is equivalent to a rectangular parallelepiped with dimensions $610 \times 440 \times 1130$ mm (length $\times$ width $\times$ height).

We observed that the wagons utilized by the towing truck system in the plant do not follow a standard layout, i.e. the positioning and number of shelves are not predetermined by the company, leaving the operator free to choose the height. That leads to the fact that frequently the internal space of the wagons are not properly utilized. It is quite common that the operator is not able to place a box on the wagon due to the shelves positions, even if the total empty space would be

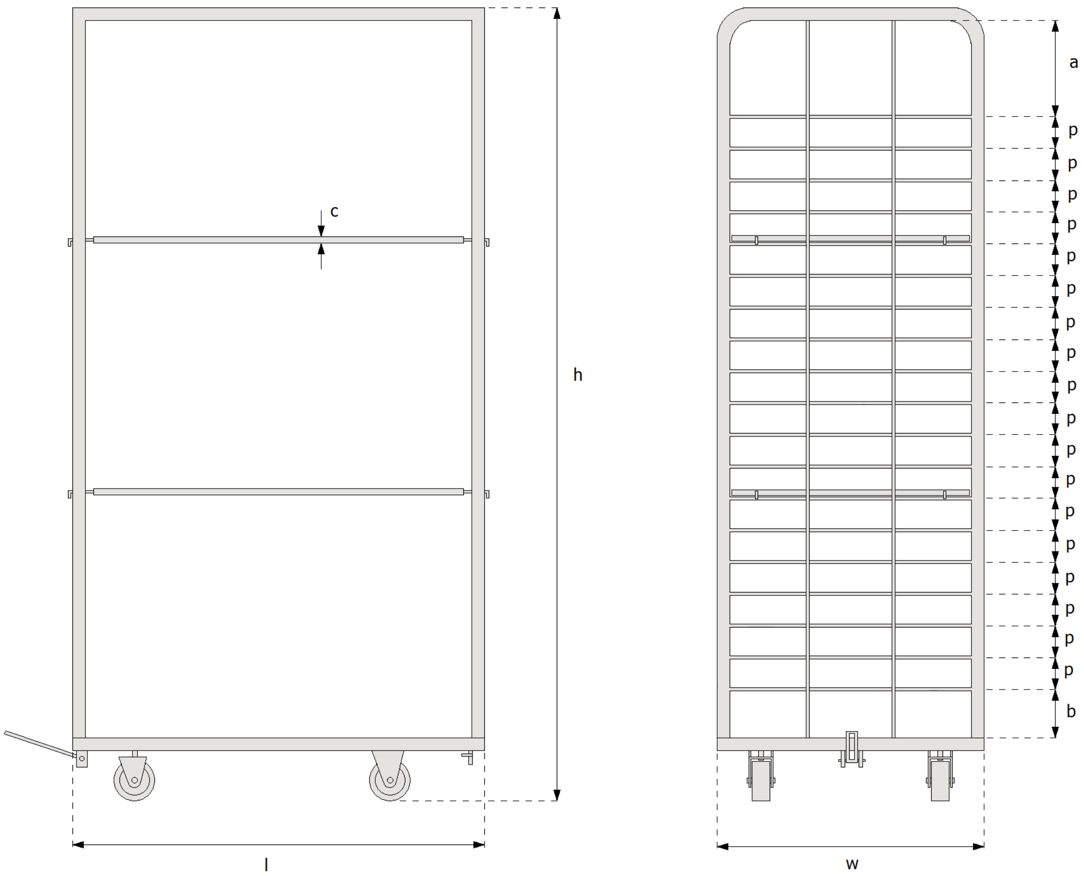


Figure 4.9: Wagon tugged by the towing truck - main dimensions

Table 4.5: Dimensional parameters of the wagon utilized in the towing truck system

Parameter	Dimension (mm)
Overall length (l)	650
Overall width (w)	440
Overall height (h)	1320
Shelf thickness (c)	10
Step between two adjacent shelf positions (p)	50
Top portion of the available space (a)	155
Bottom portion of the available space (b)	75

sufficient to store it. This motivated us to develop an analysis of how to set the height and number of shelves in the current wagons in such a way that capacity is maximized considering the dimensions of the boxes to be transported.

Considering a wagon with 2 shelves, let N_{S1} and N_{S2} be the number related to the adjustable position on which shelves 1 and 2 are positioned, being 1 the lowest position and 19 the highest position. For instance, $N_{S1} = 10$ means that shelf number one is positioned at the tenth height position from the bottom to the top. Considering that shelf $S1$ is in a lower position with respect to shelf $S2$, these two variables have then to satisfy:

$$N_{S1}, N_{S2} \in \{1, 2, \cdots, 18, 19\}, \tag{4.1}$$

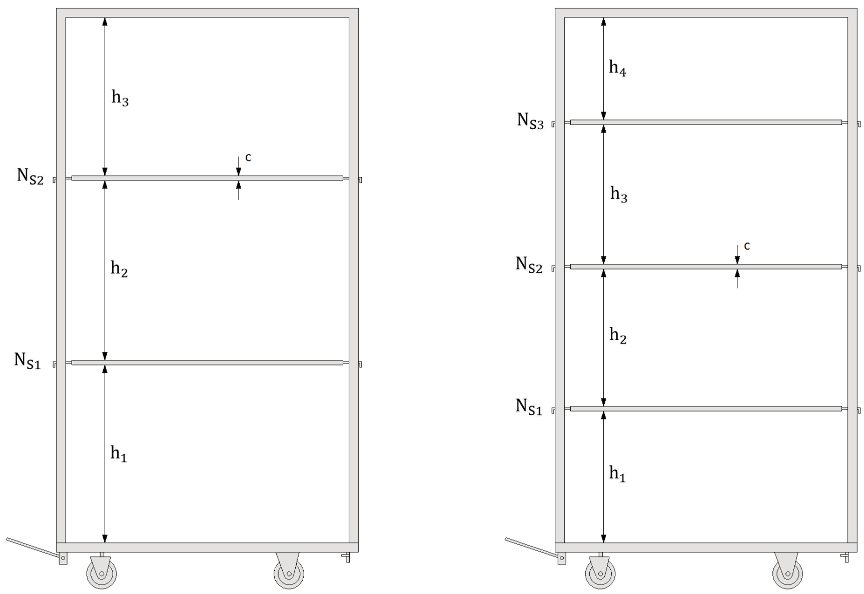
$$N_{S1} < N_{S2}. \tag{4.2}$$

In case of 2 shelves, there are three levels, with internal heights h_1, h_2, and h_3, respectively, as indicated in Figure 4.10a. These 3 parameters are then defined according to the two variables N_{S1} and N_{S2} as follows:

$$h_1 = (N_{S1} - 1)\, p + b, \tag{4.3}$$

$$h_2 = (N_{S2} - 1)\, p + b - (h_1 + c) = (N_{S2} - N_{S1}) \cdot p - c, \tag{4.4}$$

$$h_3 = (19 - N_{S2})\, p + a - c. \tag{4.5}$$



(a) Wagon in a 2-shelf configuration (b) Wagon in a 3-shelf configuration

Figure 4.10: Definition of the internal heights of each layer for both 2-shelf and 3-shelf configuration

The same reasoning may be applied to a wagon with 3 shelves, fixed at positions N_{S1}, N_{S2}, and N_{S3}. Analogously, the three variables have to satisfy the following constraints:

$$N_{S1}, N_{S2}, N_{S3} \in \{1, 2, \cdots, 18, 19\},$$

$$N_{S1} < N_{S2} < N_{S3}.$$

The internal heights of the corresponding four levels, h_1, h_2, h_3, and h_4, are indicated in Figure 4.10b. In this case, they can be expressed in terms of the variables N_{S1}, N_{S2}, and N_{S3} as

$$h_1 = (N_{S1} - 1)\, p + b,$$

$$h_2 = (N_{S2} - N_{S1})\, p - c,$$

$$h_3 = (N_{S3} - N_{S2})\, p - c,$$

$$h_4 = (19 - N_{S3})\, p + a - c.$$

Considering the 4 packaging categories that are transported in the wagons (A, B, C, and E categories), the height of the box can be either equal to 15cm (A and E categories) or 30cm (B and C categories).

Additional constraints to the problem are as follows.

- Valeo determined that B and C-category boxes cannot be stacked on the same shelf, while A and E-categories provide the possibility to place one box on another. However, only one box can be placed on another. When stacked, the grouped boxes' height equals the height of B and C-category boxes (30cm).
- Between the top of a box placed on the wagon and the bottom of the next shelf, there should be left a minimum gap $g = 4$cm required for the handling of the box by the operator when loading and unloading the wagon.

The constraints are translated into mathematical relations as follows

$$h_i \geq \begin{cases} g + 15\text{cm}, & \text{for A and E-category boxes} \\ g + 30\text{cm}, & \text{for B and C-category boxes,} \end{cases} \tag{4.6}$$

where $i = \{1, 2, 3\}$ for 2-shelf wagons and $i = \{1, 2, 3, 4\}$ for 3-shelf wagons.

The criterion utilized for the optimization of the wagon layout is the utilization of its internal capacity. It means that the best solution is the one that satisfies the gap condition, but minimizes the sum of the additional gaps beyond the minimum required gap, G_{add}. Let $g_{\text{add},i}$ be additional gap beyond the minimum required gap on level i defined as

$$g_{\text{add},i} = \begin{cases} h_i - (g + 15\text{cm}), & \text{for A and E-category boxes} \\ h_i - (g + 30\text{cm}), & \text{for B and C-category boxes} \end{cases}, \tag{4.7}$$

so G_{add} is given by

$$G_{\text{add}} = \sum_{i=1}^{N} g_{\text{add},i}, \tag{4.8}$$

where $N = 3$ for 2-shelf wagons and $N = 4$ for 3-shelf wagons.

If more than one solution have the same value of G_{add}, the best one is defined as the one that divides the additional gap over the levels in the most homogeneous way. In other words, for a given value of G_{add}, the best solution is the one that presents the lowest variability of the gaps.

The gaps variability can be assessed by means of the standard deviation of the additional gaps, defined as:

$$\sigma_g = \sqrt{\frac{\sum_{i=1}^{N}(g_{\text{add},i} - \bar{g}_{\text{add}})^2}{N}},$$

where $\bar{g}_{\text{add}} = (1/N)\sum_{i=1}^{N} g_{\text{add},i}$ is the mean additional gap over the minimum required at each level.

Therefore the problem is to vary N_{S1} and N_{S2} by respecting the constraints (4.1) and (4.2), and to calculate the corresponding internal heights h_i according to (4.3), (4.4), and (4.5). Constraint (4.6) is then verified, and solutions that do not satisfy it are excluded. The solutions are then sorted in a decreasing order in terms of G_{add}, according to the values of the additional gaps. The secondary sorting criterion is σ_g, i.e. solutions with same G_{add} are sorted in a decreasing order in terms of σ_g.

All possible solutions were computed using Matlab®(by Mathworks®). For a 2-shelf wagon, there are 171 different combinations for (N_{S1}, N_{S2}), from which 66 solutions satisfy all constraints of the problem. Three of these solutions provide the minimum possible value for G_{add}, so the best one was chosen by applying the gap variability criterion. For a 3-shelf wagon, the number of possible combinations for (N_{S1}, N_{S2}, N_{S3}) rises to 969, from which only 84 comply with the predefined constraints. In this case, 6 solutions provided the minimum G_{add}, from which the best one was picked by the variability criterion.

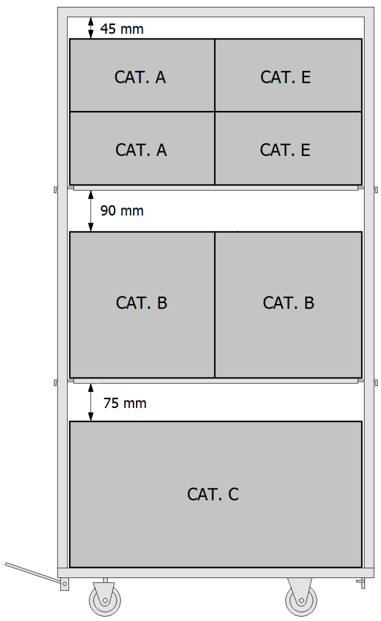
Table 4.6 shows the results of the computation of the best solution for both 2-shelf and 3-shelf wagons. Both configurations are illustrated in Figure 4.11.

Table 4.6: Main parameters of the optimized solutions for the wagon layout for both 2-shelf and 3-shelf wagons (all parameters given in mm, except N_{S1}, N_{S2}, N_{S3})

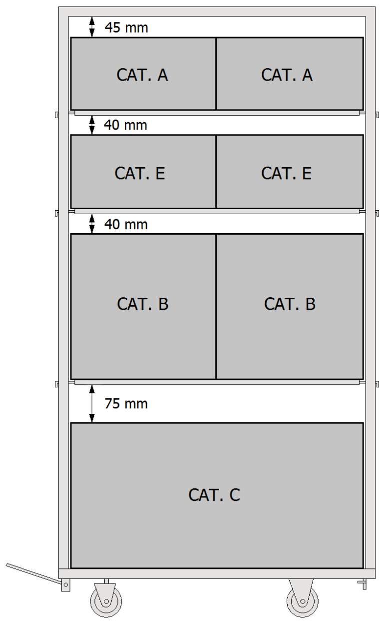
Parameter	**2-shelf wagon**	**3-shelf wagon**
N_{S1}	7	7
N_{S2}	15	14
N_{S3}	-	18
h_1	375	375

Table 4.6 - continued from the previous page

Parameter	2-shelf wagon	3-shelf wagon
h_2	390	340
h_3	345	190
h_4	-	195
$g_{\text{add},1}$	35	35
$g_{\text{add},2}$	50	0
$g_{\text{add},3}$	5	0
$g_{\text{add},4}$	-	5
G_{add}	90	40
σ_g	22.9	16.8



(a) Best solution for a 2-shelf wagon



(b) Best solution for a 3-shelf wagon

Figure 4.11: Illustration of the best layout for both 2-shelf and 3-shelf wagons for the problem's constraints

Considering the relation between the volumes of the different categories, as explained in Section 4.2, it is possible to describe the capacity of both configurations in terms of the number of category A boxes that the wagon can carry. Coincidentally, both solutions provide the same capacity of 24 category A boxes.

Therefore, the objective of maximizing the wagon's capacity under the predefined constraints is achieved in both the 2-shelf and 3-shelf configurations, so any of them could be chosen as the final one. The solution with 2 shelves, however, has an advantage with respect to the other, due to the fact that each of its three layers can store any type of boxes (from categories A, B, C, and E), while the upper levels of the 3-shelf wagon can store exclusively boxes from categories A and E. The flexibility of the first solution guarantees that a load under the maximum capacity of the wagon (equivalent to 24 category A boxes) can always be stored in it. This cannot be guaranteed to the second solution (for example, it is not possible to place three category C boxes on the wagon). For this reason, the wagon's configuration to be implemented on the towing truck optimized system is the 2-shelf solution.

4.4.1 Definition of the maximum number of wagons attached to the towing truck

In order to define the number of wagons to be attached to the main towing truck, we performed a series of tests.

In addition to the wagons utilized for placing the loads, an auxiliary wagon has also to be attached to the truck. It holds a printing machine and its battery, as well as providing a surface on which the operator can place packages while performing labeling and controlling operations. The printing machine is used to provide the label that should be stuck to the packaging before entering the FGWH area.

We performed some tests in a cornering situation. The corner in which tests were held is placed on the crossing of two drivable ways, one of which being the narrowest one on the plant. The truck was driven by two different operators. The conditions under which the tests were performed are the following:

- Number of wagons: the truck was configured with two, three, and four wagons attached to it.
- Roller: for each configuration, after the initial assessments, we performed an additional test introducing a roller to the chain of towed wagons. The roller is compatible with the dimensions of the packaging type 4203 (Figure 4.2a). The reason for testing this configuration is subsequently explained in Section 4.5.3.
- Load: we tested all the configurations under two load conditions:
  (a) Zero-load condition: no packages were placed on the wagons;
  (b) Full-load condition: all the wagons were filled to its full capacity. All 4 compatible packaging categories were placed on the wagon, as in Figure 4.11a. The total weight applied to each wagon was approximately 80 kg.

The operators were asked to drive at a speed about 75% of the truck's nominal speed $v = 8\text{km/h}$. Valeo trains its operators to reduce substantially the truck's speed when performing curves. The tests were performed at a higher speed with respect to the one recommended by Valeo in cornering situations. Therefore, the conditions under which the test was made are more severe than the usual ones.

At each configuration, two evaluation criteria were assessed: the difficulty to maneuver the truck and the possibility of dropping boxes while performing the curve. The difficulty to maneuver was physically evaluated in case of any part of the towing system touched the borders of the roads, but the operator's subjective opinion was also taken into account.

By considering the previously mentioned criteria, we defined two configurations as the maximum allowed number of wagons to be towed by the truck. The top views of both configurations are illustrated in Figures 4.12 and 4.13. The first one is a wagon-only configuration; it includes a maximum of three wagons in addition to the auxiliary one. The second one combines two wagons and a roller (at the end of the towed chain). These two configurations are, from this point, considered the standard ones according to which the towing truck can operate.

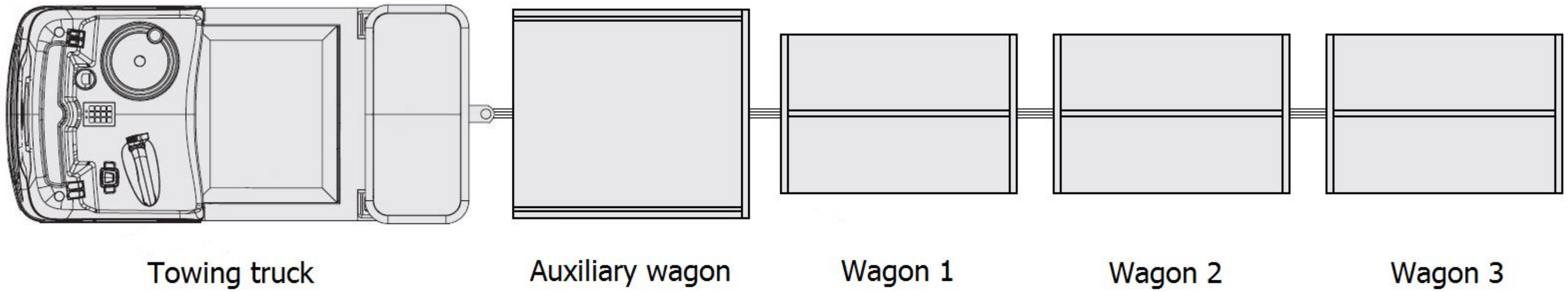


Figure 4.12: Towing truck at the 3-wagon configuration

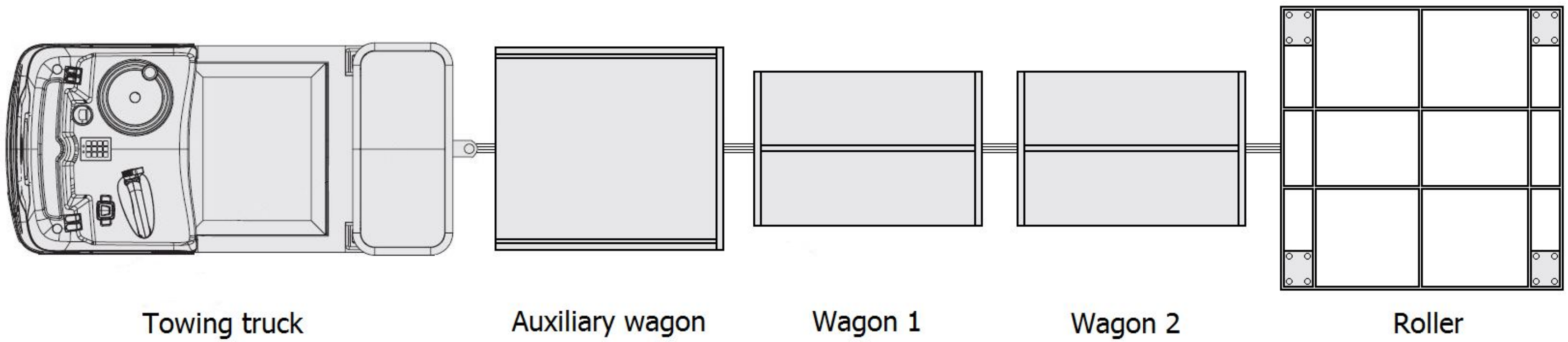


Figure 4.13: Towing truck at the 2-wagon one-roller configuration

4.5 Towing truck's routes definition

As mentioned at the beginning of this chapter, the objective of this system alternative is to reduce the operational cost directly related to the material handling task. We propose to rationalize the picking up routes performed by the towing truck in order to reduce them to the minimum required, in such a way that the output volumes from production are effectively drained while reducing the total time spent by the truck's operator on the collection activity. The next sections will explain the logic on which the proposed solution is based, as well as detailing the assumptions and limitations of the system.

4.5.1 Cells' production volume analysis and cell grouping

Once the wagon's layout is defined, it makes it possible to compare the production volumes of the cells even if they generate different types of boxes as output. From now on, the production volumes will be described in terms of wagons per unit of time, i.e. the number of wagons that are filled by the packages generated from the cell in a given period of time. This is calculated taking into account the capacity of the wagon expressed in terms of the number of boxes for each of the packaging categories. Those relations are expressed in Table 4.7.

Table 4.7: Wagon's capacity in terms of the different categories of boxes

Category	**Wagon's capacity [number of boxes]**
A	24
B	6
C	3
E	12

As mentioned in Section 4.2, there are three different category-D packages, corresponding to Valeo reference codes 4203, 419, and 50. At the beginning of the project, only the first one was handled by means of the towing truck because a roller similar to the one in Figure 3.7a is available with dimensions suitable for its fitting. This package is used exclusively in cell I20. However, 419 and 50 packages, due to their larger base, would not fit the same roller and so a hand pallet truck is employed for its movement. These packaging materials are exclusively used in cells DV09, DV11, and DV15. For this reason, these cells are handled separately by the hand pallet truck, while all the other workcells are managed through the towing truck system.

Considering the two possible configurations for the number of wagons discussed in Section 4.4.1, it is clear that, from the truck's capacity viewpoint, it is possible to consider one category D box equivalent to one wagon, since it substitutes a wagon from the truck's first configuration to the second one. So, by combining this equivalence and the relations from Table 4.7, it is possible to describe all workcells' production volumes in terms of wagons per unit of time.

Table 4.8 shows the average production volumes in this new unit of measure for each of the workcells (denoted as $q_{w,i}$), as well as the mean time interval between the production of two consecutive boxes (denoted as Δt_i). In order to calculate the values shown in the table, the daily production volumes in terms of each packaging category reported in Table 4.4 were rounded up to the nearest integer and then converted to the daily number of wagons from the relations defined in Table 4.7.

Table 4.8: Average daily production volumes of the workcells in terms of the number of wagons to be transported from them, and the mean time interval between the production of two consecutive boxes

Cell	**Production volume** ($q_{w,i}$) **[wagons/day]**	Δt_i **[hours]**
I20	6.00	2.7
I03	3.29	0.4
I39	3.00	1.8
I08	2.67	2.0
I34	2.58	1.0
I32	1.83	1.5
I23	1.33	3.2
I27	1.17	2.3
I05	1.08	2.0
I33	1.08	2.0
I02	1.00	5.3
I40	1.00	5.3
I19	0.92	1.6
I17	0.83	3.2
I24	0.83	3.2
I01	0.79	2.3
I26	0.67	8.0
I16	0.63	2.7
I28	0.42	4.0
I07	0.25	2.7
I25	0.25	5.3
I21	0.21	8.0
I04	0.17	16.0
I12	0.17	16.0
I15	0.17	16.0
I35	0.17	16.0
I18	0.17	16.0

The general guidelines followed to define the routes through which the towing truck is required to drive are described at this point. The purpose of this analysis is to subdivide the cells into groups, according to a predefined rule, so that the towing truck can handle exclusively their output materials in one of its routes (i.e. the route from the FGWH to the production area, and then coming back to the initial point). For each group, a route (sequence of cells to be handled and path to be followed) and a frequency of operation (time interval between two consecutive routes) are defined.

The route definition process is iterative and is performed according to the following steps:

1. From Table 4.8, cells are sorted decreasingly in terms of the number of wagons produced. An initial subdivision of the cells is then performed according to that sorting parameter. Three groups, defined as A, B, and C, are created by putting together cells with high, medium and low production volumes.

2. This initial division is then improved by taking the physical position of each cell into account.

3. An initial value is set as the number of times a route j ($j = \mathrm{I}, \mathrm{II}, \mathrm{III}$) is performed per day ($n_j$). The time between the starting of two consecutive executions of a route j is then calculated as

$$\Delta t_{\mathrm{R},j} = \frac{T_w}{n_j}.$$

4. The total production volume generated by the cells that belong to group j during the time interval $\Delta t_{\mathrm{R},j}$ is calculated as

$$q_{\mathrm{tot},j} = \sum_k q_{\mathrm{d},k} \frac{\Delta t_{\mathrm{R},k}}{T_w},$$

   where $q_{\mathrm{d},k}$ is the average daily production volume from cell k (expressed in terms of units of wagons) and T_w is the total working time per day ($T_w = 16$ hours/day).

5. Two characteristics are evaluated, namely:

   (a) $q_{\mathrm{tot},j}$ should be as close as possible to the total allowed capacity of the towing truck (i.e. 3 wagons), but cannot exceed it. $q_{\mathrm{tot},j}$ can be changed by changing n_j.

   (b) $\Delta T_{\mathrm{R},j}$ should be larger than the average time between two consecutive boxes produced by a cell (Δt_i), to avoid that the truck passes by a cell when has no box to be transported.

6. If any of the conditions 5 (a) and (b) is not satisfied, the process should restart from the first step, redefining the groups. If both conditions 5 (a) and (b) are satisfied, other grouping configurations should be computed so that they can be compared in terms of predefined optimization criteria.

The initial optimization criterion is the total number of routes to be performed per day, which should be minimized. It is defined as

$$N_r = \sum_j n_j.$$

Considering that the number of cells to be handled is 26 (excluding the DV cells), the number of possibilities for configuring the groups are of order 10^{12} configurations. The computation of all the possible routes would be too complex to be handled, so only some possible solutions were individually set. If cell sequence definition would not have been taken care of, the minimum number of routes to be performed in a day, given the daily volume to be transported, is

$$N_{r,\min} = \left\lceil \frac{\sum_i q_{w,i}}{C} \right\rceil = \lceil 10.85 \rceil = 11,$$

where $C = 3$ wagons is the towing truck's allowed capacity. Therefore, we consider that solutions that provide $N_r = N_{r,\min} = 11$ are acceptable.

The secondary optimization criterion is similar to the one applied to the wagon layout optimization process. It consists in choosing the solution with the lowest variability in terms of the amount of load transported. The parameter analyzed is then the standard deviation of the amount of load transported in one day, σ_q, and the best solution is the one that provides the lowest value.

Three possible solutions for the grouping problem have been individually determined by also taking the physical disposition of the cells into account. These three solutions are indicated in Figures 4.14, 4.15, and 4.16. The different colors indicate all the cells that belong to the three groups I, II, and III.

The three different cell groupings provide the results shown in Table 4.9. All these solutions satisfy the transporting capacity of the towing truck (i.e. $q_{\text{tot},j} \leq C$), and provide the same overall average capacity utilization, defined as the ratio between the total amount of load to transported and the capacity of the wagons utilized in a day, i.e.

$$\bar{u} = \frac{\sum_j n_j \cdot q_{\text{tot},j}}{C \cdot \sum_j n_j} = 94\%.$$

Table 4.9: Main results of the three chosen solutions to the cells grouping problem

Parameter	**Solution 1**	**Solution 2**	**Solution 3**
n_{I}	7	6	7
n_{II}	3	4	3
n_{III}	1	1	1
$q_{\text{tot,I}}$	2.87	3.00	2.89
$q_{\text{tot,II}}$	2.75	2.58	2.69
$q_{\text{tot,III}}$	2.83	2.83	2.83
σ_q	0.052	0.194	0.086

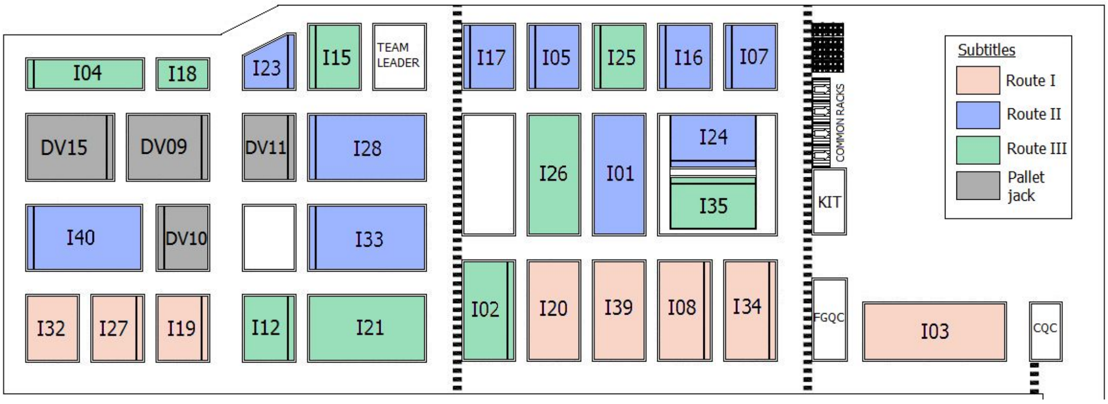


Figure 4.14: Solution 1

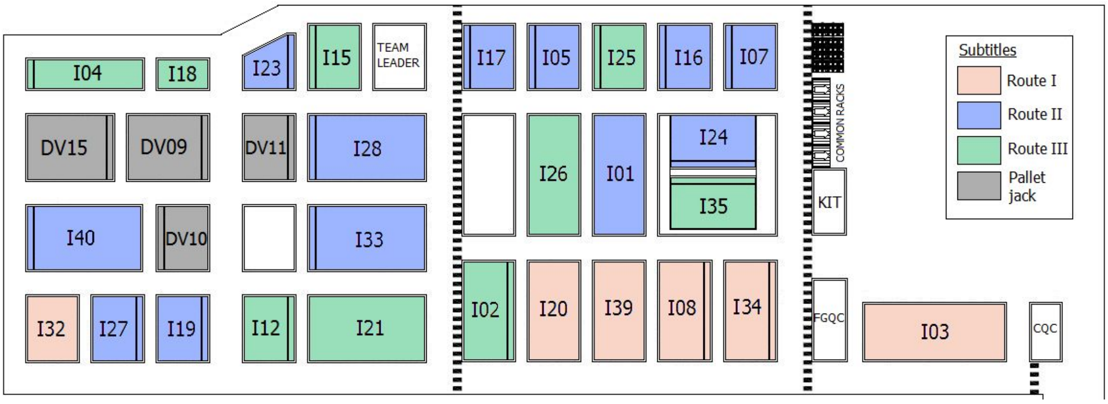


Figure 4.15: Solution 2

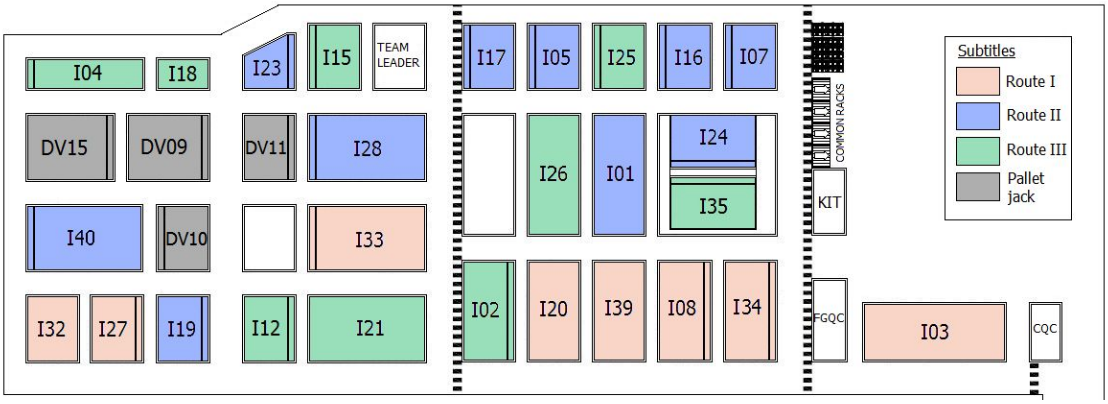


Figure 4.16: Solution 3

The selected solutions provide the same value for the first optimization criterion ($N_r = 11$), so the best solution is defined by the secondary criterion (minimum σ_q). It can be concluded then that solution 1 is the best one according to the selected optimization criterion.

4.5.2 Methodology for estimating the time required for the completion of the transporting activities

The activity of transporting goods by the towing truck operator can be subdivided into repetitive, single tasks, in such a way the time required to perform each individual activity can be estimated. We propose to define 11 simple activities whose singular duration can be estimated by the observation of the work of Valeo's operators, and then use this model to estimate the duration of a route by the towing truck as a combination of those activities.

The proposed individual activities are the following:

- A1 - Operator starts next to the truck, stands on the truck, starts its motor and accelerates it until the nominal speed;
- A2 - Operator stars standing on the truck, drives until the next stop at nominal speed; (*it does not include the deceleration time*)
- A3 - Operator starts standing on the truck at driving at nominal speed, decelerates it until full stop and gets off the truck;
- A4 - Operator starts standing on the truck driving at nominal speed, decelerates in order to perform a curve (changes direction of movement in 90^o) at a reduced speed, and accelerates it until nominal speed is again reached (*an additional time is added to the time of activity A3 due to speed reduction while performing curves*);
- A5 - Operator starts standing next to a package and picks it up;
- A6 - Operator starts standing, walks at a constant speed and stops at the next stop;
- A7 - Operator starts with a package on his/her hands and drops it off in a specific nearby area;
- A8 - Operator starts standing on the truck, performs a 180^o turn at a reduced speed;
- A9 - Operator starts next to the truck, picks up a package from the auxiliary wagon, performs a labeling and checking operation, and places it on a wagon;
- A10 - Operator starts next to the truck, detaches the loaded wagons from the truck and attaches empty ones to it;

- A11 - Operator starts next to the truck, walks to a specified area, picks up an empty 4203-type package, places it on a roller and attaches it to the towing truck.

The whole route can be subdivided into a set of activities from the previous list. In general, the route consists of driving from the FGWH to the selected cells (activities A1, A2, A3, and possibly A4), picking up packages (A5, A6, and A7), performing labeling activities (A9), dropping off and picking up packages at the FGQC station (A5, A6, and A7, once again), driving back to the warehouse and maneuvering it to the initial position (A8), and changing loaded wagons by empty ones (A10 and A11).

The mean time to execute the activities was estimated by the average of the observed times in five repetitions of each activity. For activities A2 and A6, the time was measured for a 10-meter displacement. The times were collected by means of a chronometer with a resolution of 0.01 s. Due to the dependency of the data collection on the response time of the measurer, the measured times were recorded with a resolution of 0.5 s. We noticed that the variability of the observed values for each activity is small. In fact, the difference between the maximum and minimum observed values for each activity is smaller than 20% of the average value. Table 4.10 shows the estimated mean times of all the activities.

Table 4.10: Estimated mean times of activities A1,. . . , A11

Activity	**Estimated mean time (s)**
A1	4.5
A2	4.5 [(1)]
A3	5.0
A4	3.5
A5	1.5
A6	15.0 [(1)]
A7	1.5
A8	10.5
A9	29.0
A10	42.5
A11	21.0

[(1)] For a 10-meter displacement.

4.5.3 Routes definition

Valeo provides a set of security standards to be applied to all its manufacturing sites. Some of them concern the use of transporting equipment like the towing truck, providing a method to be followed while determining the roads on which it can go through, according to simple parameters. It is not the scope of this thesis to discuss the methodology, but Figure 4.17 shows the drivable ways on the manufacturing area according to the Valeo security standards. The route definition problem should then take into account only the drivable roads.

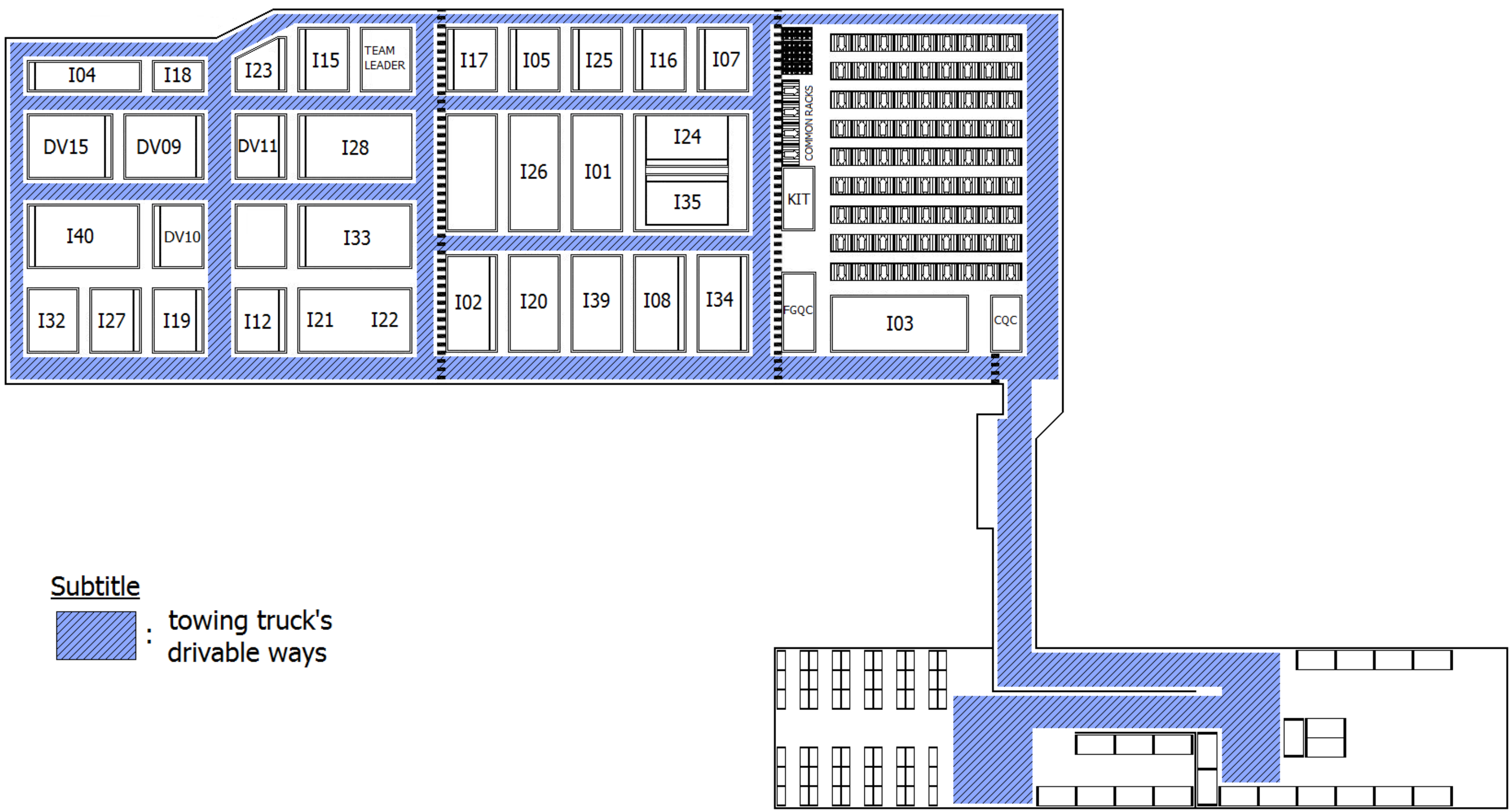


Figure 4.17: Simplified layout highlighting the ways on which the towing truck is allowed to drive according to the company's security standards

Once again, due to the complexity of the routing problem (too many possible routes can be computed), two possible routes were subjectively defined for each group. The company did not want to invest excessive time in developing a new routing definition methodology or even applying an algorithm from the literature. The choice took into account the closeness of the cells and the subjective effort to reduce the total distance traveled. Figures 4.18 and 4.19 show the two routes solutions for group I, Figures 4.20 and 4.21 for group II, and Figures 4.22 and 4.23 for group III.

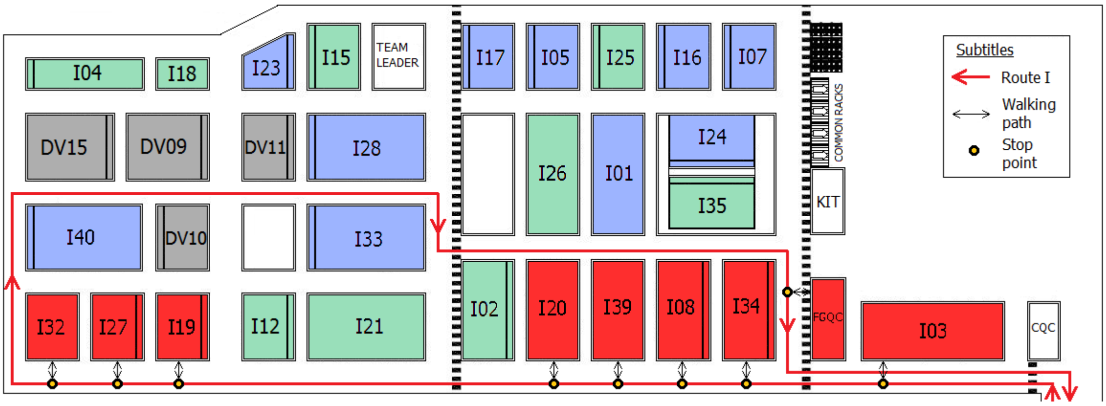


Figure 4.18: Alternative 1 for the route to be followed by the truck in order to pick up boxes from group I cells

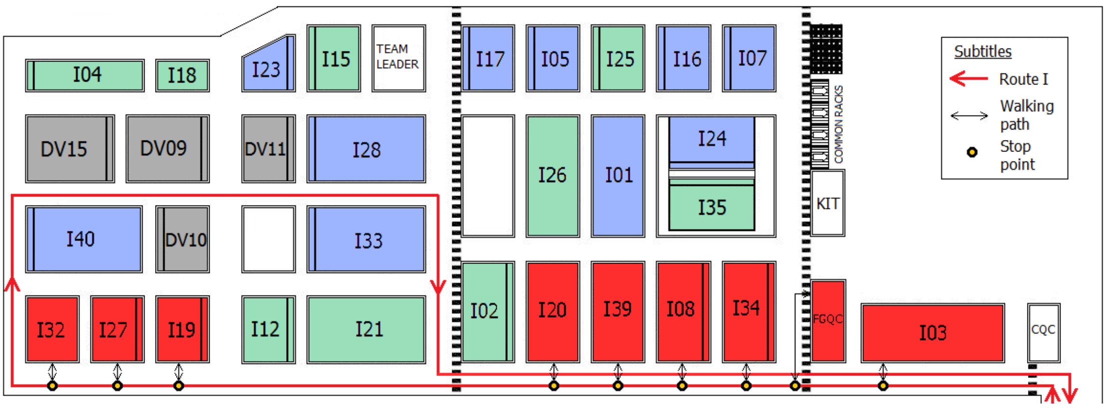


Figure 4.19: Alternative 2 for the route to be followed by the truck in order to pick up boxes from group I cells

The choice between the two route alternatives for each cell group is based on the minimum total time required for the completion of the route. The methodology used for the time calculation is the one reported in Section 4.5.2. All distances are measured and the position in which the towing truck stops at each cell is identified in Figures 4.18, 4.19, 4.20, 4.21, 4.22, and 4.23. The number of boxes picked up in each cell is given by the ratio between the average daily production volume divided by the time interval between two consecutive routes.

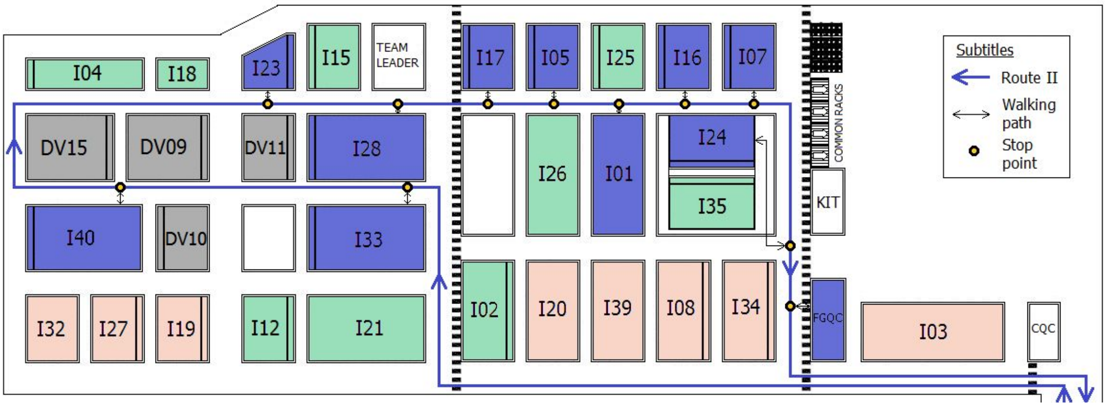


Figure 4.20: Alternative 1 for the route to be followed by the truck in order to pick up boxes from group II cells

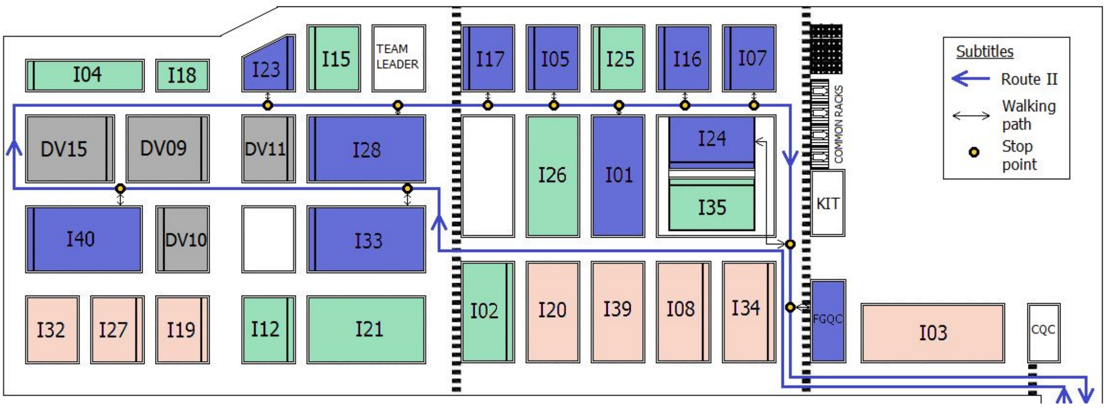


Figure 4.21: Alternative 2 for the route to be followed by the truck in order to pick up boxes from group II cells

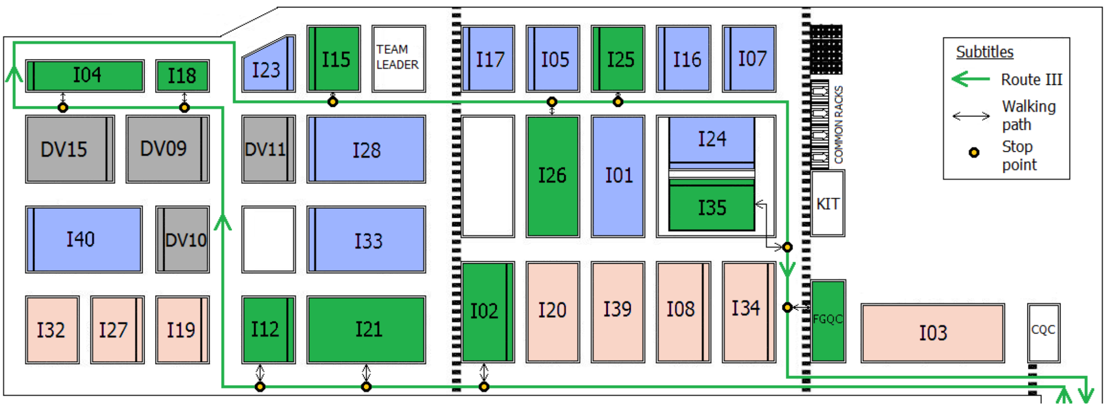


Figure 4.22: Alternative 1 for the route to be followed by the truck in order to pick up boxes from group III cells

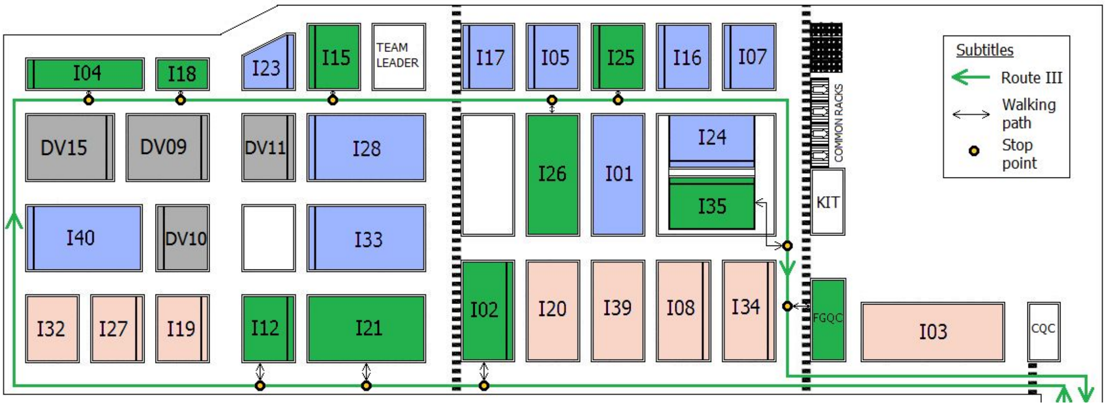


Figure 4.23: Alternative 2 for the route to be followed by the truck in order to pick up boxes from group III cells

The total time required for the completion of each route alternative is shown in Table 4.11. The alternative with lower total time between the two is the selected one.

Table 4.11: Total time required for the completion of each route alternative

Cells group	Alternative	Total time (min)	Choice
I	1	18.18	Selected
I	2	18.47	Discarded
II	1	19.16	Selected
II	2	19.22	Discarded
III	1	11.75	Discarded
III	2	11.53	Selected

The single route time can be multiplied by the number of routes performed per day, resulting in the total time spent on the transportation of FGs from the cells to the warehouse. Considering the three different routes, this activity should be performed in 196.2 minutes per day. Table 4.12 reports the summarized results.

Table 4.12: Individual time required for collecting FGs-type boxes through routes I, II, and III, and the total collecting activity time

Route	Total time
I	7×18.18=127.3 min
II	3×19.16=57.4 min
III	1×11.53=11.5 min
	196.2 min

4.6 Components empty packaging material

As mentioned in Section 4.1, in addition to the transportation of FGs, we propose that the optimization process described in this chapter would be extended also to the transportation of components empty boxes after their use by the cells. This section is dedicated to extending the optimization process to this second activity.

Components are either packed with Valeo's plastic boxes (codes V35, V36, and V37) or carton boxes (codes 209, 210, and 0018). The major part of components is packed with plastic boxes (about 80%). Carton boxes, after the use of its components, are discarded in a specific area within the production area. On the other hand, plastic boxes are reusable and have to be returned to the suppliers. Therefore the activity of transporting empty boxes to the low rotation warehouse is applied only to the plastic packaging material.

The analysis of the output rate of those boxes from the cells is hard to be performed because it cannot be determined in a precise way. Ideally, since the production rate of FGs is known, the output rate of empty boxes from components could be determined if the following information is known: the BOM of each FG, the quantity per box and type of packaging material for each component. Although the BOM is known, the information concerning the components is not completely accurate. For that reason, it is necessary to estimate the output rate.

The method for estimating the previously cited rate was by observation of boxes at the end of each towing truck's route. Note that the measurements were performed on the current material handling scenario (not the optimized one). The type and number of boxes were recorded for 10 different routes. Each box was labeled as a component or FG type. The data is shown in Table 4.13.

Table 4.13: Recorded data from 10 observations of the arriving boxes after a towing truck route (quantities in number of boxes)

Observation		**FG-type**					**Component-type**				
	Cat.	*A*	*B*	*C*	*D*	*E*	*A*	*B*	*C*	*D*	*E*
1		1	3	1	0	1	5	3	2	0	0
2		2	1	2	0	0	3	2	3	0	0
3		0	0	0	1	1	3	3	2	0	0
4		4	4	0	0	1	6	2	2	0	0
5		2	3	1	0	0	3	2	3	0	0
6		0	1	0	1	0	4	1	3	0	0
7		4	1	2	0	0	4	4	1	0	0
8		1	0	0	1	0	4	2	2	0	0
9		2	3	1	0	0	1	2	3	0	0
10		2	2	2	0	0	2	3	2	0	0

From the data shown in Table 4.13, on average 43% (in terms of volume transported) of the arriving boxes are FG-type and 57% are component-type. In other words, the transported volumes of component-type packaging materials are 33% higher than FG-type ones.

Due to the previously cited lack of information regarding consumption volumes of individual components, it is suggested that a simplification is made under the following hypothesis: during a time frame Δt, if a cell produces a volume V of FG-type boxes, in that same Δt it generates a volume of $1.33V$ of component-type boxes (based on the proportion from Table 4.13).

Under this hypothesis, we propose that the towing truck performs routes dedicated exclusively to component-type empty boxes. It would utilize the same routes defined in Section 4.5.3, but with a higher frequency during the day.

Using the same notation described in Section 4.5.1, in order to match the new output rate of material, the routes I, II, and III would be carried out according to the parameters of Table 4.14. The configuration results in an average utilization of the cart's capacity of:

$$\bar{u} = 85\%.$$

Table 4.14: Routes parameters and results for the component-type boxes collection by the towing truck

Route	n_j	Δt	$q_{\text{tot},j}$	u_j
I	10	1.6	2.69	90%
II	4	4.0	2.61	87%
III	2	8.0	1.71	57%

For the calculation of the time required to complete each route, the same logic and coefficients described in Section 4.5.2 are utilized. It is important to highlight that, for component-type boxes, there is no need to execute activity A9 (labeling and checking operation). The results are shown in Table 4.15.

Table 4.15: Individual time required for collecting component-type boxes through routes I, II, and III, and the total collecting activity time

Route	**Total time**
I	10×8.19=81.9 min
II	4×8.56=34.2 min
III	2×6.73=13.5 min
	129.6 min

Chapter 5

Application of an AGV system for material handling

Valeo has decided to evaluate the implementation of an AGV system for the transportation of goods in Santena. The use of this automated system has been increased over the last years by the Group in its plants through the world.

The application of this kind of system may be easier for a manufacturing plant yet to be constructed. When the layout is not yet defined, it can be designed to maximize the AGV system capabilities. For example, if it is desired to have a fully automated system, gravity flow racks inside the cells would have to be designed especially for that task. If the layout is not yet defined, the racks configuration and positioning can be easily changed and virtually tested until a good solution is found. On the other hand, when dealing with a pre-existing layout, the new racks may have different dimensions with respect to the current ones, which may force the current layout of production stations to be modified, and that may not be always possible. A complete relayout of the plant would be very time-consuming, both in planning and execution phases. In addition, the complete substitution of all racks for new ones may indicate a significant loss of money previously collected for their purchase.

Considering that the Santena plant has a pre-existing layout, and by taking into account the difficulties related to an intensive relayout of the manufacturing system, the proposed AGV solution should avoid as much as possible a deep modification on the current plant layout.

5.1 Scope of the system

Although the AGV could perform all kinds of material transportation from and to cells, Valeo has decided to implement it only to a share of all the transportation activities. The initial system would be designed to perform two activities:

- transportation of FGs from cells to the FGWH;
- transportation of components empty plastic boxes after their use in a cell to a specific deposit area within the low rotation warehouse.

Note that these are the same studied activities as in Chapters 3 and 4. Other transporting activities, such as material feeding for cells, would not be performed by the AGV system at this time. Once the performance of the AGV is evaluated and validated by the company, the implementation of its service to a wider set of activities could be considered.

5.2 The offered products and accessories

Valeo chose the company Indeva to be a possible provider of the equipment and the installation of the AGV system in the plant. Indeva is part of an important Italian industrial group (the Scaglia Group), which provides products and solutions in the fields of textile machines, power transmission devices, automation and robotics, and material handling and lean manufacturing solutions. Indeva, created in 1838, was the foundation of the Scaglia Group, and currently sets its headquarters in Val Brembilla (in Bergamo province), in Italy. Its activities though are worldwide, including branches in Germany, France, UK, Sweden, USA, and China.

There are other AGV manufacturers (or sales representatives) in Europe, such as SSI Schaefer (Germany), Dematic (U.S.A.), ULMA Handling Systems (Spain), and AVT (Belgium). Indeva was picked up by Valeo managers as a possible provider of the system because of the characteristics of the products (compatible with Valeo's volumes and transporting capacities required), and also because the Santena plant is close to Indeva's headquarters (less than 250 km distant). The proximity to the AGV system supplier may provide a quicker and more present assistance if problems are detected.

Indeva provides two types of AGVs:

- Tugger AGV: it is a vehicle designed to tow a train of trolleys. The car is illustrated in Figure 5.1a. This solution is offered in two versions, one with a maximum towing capacity of 750 kg and the other one of 1,500 kg.
- Tunnel AGV: the vehicle is designed to move trolleys or carts by positioning itself beneath the cart to be moved and activating a pin-hook system that attaches the load to the vehicle. The solution is illustrated in Figure 5.1b. Its maximum towing capacity is 750 kg. This solution provides the possibility of releasing a full trolley and hooking an empty one automatically, without the need for any human work.

(a) Tugger AGV (b) Tunnel AGV

Figure 5.1: The AGV solutions provided by Indeva

The use of these two solutions is exemplified in Figures 5.2a and 5.2b. The figures show two real applications of the system and possible trolley layouts. Both solutions work with magnetic tapes as the guidance method for the vehicles, i.e. a tape is applied to the floor and the AGVs are programmed to follow it while moving.

(a) Tugger AGV (b) Tunnel AGV

Figure 5.2: Real application of the AGV solutions provided by Indeva

In addition to the two AGV types, Indeva offers a set of accessories to the system [53]:

- Battery trolley: accessory to change batteries automatically. The battery slides from the onto and from the AGV by means of rollers, excluding the need for human assistance for that operation.
- Trickle charger: installation of charging points throughout the plant. The AGV, while passing through those points, charges its battery.

- Magnetic markers: indicators made of magnetic material which are glued to the floor in order to indicate to the AGV the position on which it should stop to perform a task.
- RFID (Radio Frequency Identification) tags: system capable of determining the univocal identification of each AGV on the plant. It is useful for the management of multiple AGVs and traffic avoidance.
- Supervisor and controller: the unit receives information from the AGVs regarding their position and work parameters and analyzes the data. Its function is to control the AGVs and all interconnected devices, the vehicles position, its battery level and other parameters, as well as to assign tasks to the different AGVs.
- WiFi device: it is possible to equip the AGV with a WiFi device in order to allow communication between the vehicle and other interconnected devices.
- WiFi Start-Box: it consists of push buttons that start an AGV. It can either be installed on the AGV or near an operator's position to improve ergonomics.
- Electronic Kanban: it allows to assign pre-set tasks to AGVs by means of the activation of a specific switch from a remote position.
- Custom trolleys: Indeva offers customized trolleys according to the company's needs.

5.3 Proposition of AGV system configuration

As discussed at the beginning of Chapter 5, it may be more difficult to implement an AGV system solution to a preexisting manufacturing facility than to conceive a new plant designed for the interaction with this automation solution. The idea is then to find a solution that would require a low level of adaptation of the current plant layout, even if the solution would not provide the highest automation level of the MHS. In other words, the proposed solution seeks to have a small impact on the current layout and yet provide a significant improvement in the automation level of the manufacturing plant.

Having in mind the previously cited objective, the chosen vehicle type is the towing AGV. This choice is due to the fact that it is a simpler solution with respect to the tunnel AGV, which includes an automated pin-hook system and consequently demands a more complex attaching and detaching system. Obviously, this complexity is followed by an increase in the purchasing price of the vehicle. Magnetic tapes would be applied to the floor in specific areas, including magnetic markers in key points of the plant (cells, drop-off point, etc.).

Each manufacturing cell would be provided with an Electronic Kanban system, as described in Section 5.2. The panel would include three buttons: the first one, when pushed, would indicate to the AGVs that one or more boxes are waiting to be transported from that cell - it would then pick up the boxes when possible.

The second one, when the AGV is stopped at a cell, would indicate that it is free to perform the next task. And the third one would send a command to go to the drop-off point (in the FGWH).

The same wagons currently utilized by the towing truck (discussed in Section 4.4) would still be used for this system solution. This means that they would have to be filled with boxes in a manual way by an operator from the manufacturing cells they are collecting the boxes from. Consequently, the AGV has to remain stopped at the station until the boxes are placed on its wagons and the operator pushes the button that allows it to perform the next task. Note that, by using the current wagons, the AGV is not capable of evaluating the volume it is transporting. The AGV, even if fully loaded, would not go to the drop-off point until an operator pushes the specific button to that task.

Another feature is introduced in order to increase the AGV system's performance. In Section 4.5.2, we cited the labeling activity that has to be performed once a box is taken from a cell. This activity is responsible for a significant portion of the total time spent on the material handling activity. We propose the introduction of a new labeling system, in which the label that is attached to the box on the cells is already compatible with the one used for storing and shipment. The new system makes unnecessary the relabeling activity, reducing significantly the stopped time of the AGV on the cell.

The only aspect yet to be defined is the number of AGVs necessary to handle the volumes to be transported. This definition will be discussed later in Section 6.3.

5.4 Evaluation of the human labor activities involved in the proposed AGV system

As mentioned in Section 5.3, the proposed AGV solution was chosen under the objective of providing a significant increase in the automation level of the material handling activity, at the same time as it seeks to have a low impact on the current plant layout. The proposed AGV system does not provide a totally automated solution, because of the dependency on human activities for specific tasks, such as material loading and unloading activities, pushing buttons in the Kanban system, etc. The objective of this section is to estimate the time required for the completion of activities performed by Valeo's operators directly related to the AGV system.

The activities that require human assistance for the AGV system's operation are reported below:

- Loading materials onto the AGV's wagons: cells operators are responsible for placing the materials on the AGV's wagons.
- Unloading materials from the AGV: a warehouse operator is responsible for detaching all the filled wagons from the AGV and replacing them with empty ones for its next collection route.

- FGs label scanning: the label attached to finished product packages has to be scanned in order to update its stock in Valeo's information system. The scanning is performed by a warehouse operator.

These three activities are subdivided into individual tasks, whose time for completion is estimated as follows:

- Loading materials onto the AGV's wagons:
  - (a) **aI**: Each time the AGV stops at a cell, the cell operator stops production activities, goes towards the vehicle, place the boxes on its wagons, pushes the Kanban button and comes back to the initial position. The time required for the movement of the operator (from origin to vehicle plus coming back) and pushing the Kanban button is estimated as 20 seconds. This time is to be accounted for each AGV's pick-up stop.
  - (b) **aII**: In addition to the previous time, an estimated 10 seconds time is added for each box picked up, accounting for the loading activity and considering that the cell operator is already standing by the vehicle.
- **aIII**: Unloading materials from the AGV: when the AGV stops at the warehouse, an operator stops warehouse activities, goes towards the vehicle, detaches the filled wagons, attaches empty ones to the vehicle, and comes back to the initial position. The time required for the completion of all these activities is estimated as 50 seconds. This time is to be accounted for each AGV's pick-up stop.
- **aIV**: FGs label scanning: we consider that the scanning activity is to be performed after the unloading task. Considering the operator standing by the wagons, we estimate a 6 seconds time for each box to be scanned. Note that the scanning is done only in FGs boxes (not for components empty boxes).

Chapter 6

Modeling and simulation of alternative material handling system configurations

After analyzing the three possible systems for the transportation of FGs and component's empty boxes, the performance and the cost of each alternative should be computed and compared.

We propose a simple model capable of simulating roughly the performance of each of the three systems. The next sections will explore the assumptions under which each model is constructed, as well as its limitations. These models are then translated into a Matlab® code. The R2015a Matlab® version was used to simulate the codes. The resulting calculations will be shown in the following sections.

All simulations are held for a single day of work (considering two shifts). The input data for the simulations is a list of every FGs box that is produced in a day and the time at which it is considered available to be transported to the warehouse. The data refers to a real working day in regular conditions. Ideally, it would be interesting to have real data on a series of days so that the different systems performance could be tested under different input volumes. It was not possible though because the data available was collected on a single day. Valeo was able to provide data regarding the FGs and the quantities that were produced in a single day, but there was no information about the distribution of the production during the day. The exact time each FG package was produced had to be individually measured (a very time-consuming activity), so the time collection was performed for a single day. Additionally, in Section 4.6, we mentioned the relation between produced volumes of FGs packaging material and components empty boxes. Note that the available data regards the volumes of *FGs* produced and the time in which each of them was released from cells. There is no information, though, regarding when *components* empty boxes are released from cells, so it should be someway estimated.

6.1 Alternative 1 - Current material handling system

We propose a simplified model to evaluate the performance of the current MHS. The model assumes the following hypotheses:

- As mentioned before, there is no available information on when each component empty box is released from the cells, so it has to be estimated somehow. Given that the volume of components empty boxes is 33% larger than FGs ones, we make the following assumption: when a FG box is produced, one component empty box plus a fraction of 0.33 box is released from the cell (we consider a time shift of 5 minutes between the FG production and the component empty box release). We consider that the complete box is ready to be picked up, while the virtual 0.33 box remains as a credit on the cell. When the next box is produced, another fraction is summed to cell's credit. When it reaches the value 1, a new empty box is considered ready to be picked up.

- As mentioned in Section 4.4, due to a bad choice of the position of the shelves on the wagons, its capacity cannot be fully utilized. For simplification's sake, we consider that the capacity of this solution is reduced by 10% with respect to the optimized wagon layout.

- In Section 3.5, from observations of the working methods of the employees responsible for this task, we evaluated that, in order to pick up FGs and components empty boxes from cells, on average 34 routes are performed each day (during two shifts), with an average duration of 15.7 minutes. The model considers the average values, i.e. 34 routes are performed each day, evenly spaced in terms of time during the 16 hours working time, all with the same duration.

- The total queued volume to be picked up from cells increases as time passes between two consecutive truck's routes. When a route is to be started, we consider that the truck goes through all cells and picks up every box it can (up to its capacity). The total queued volume is considered to drop uniformly during the route.

The simulation results are reported in terms of the following indicators:

- Average utilization of the truck's transporting capacity ($\bar{u}$): average percentage of the total available space for transporting boxes effectively used. The indicator is singularly measured every time the truck unloads at the warehouse; $\bar{u}$ is the average value of the singular measurements. It is written as a percentage - no unit of measurement associated.

- Average total queue ($\bar{q}_{\text{tot}}$): the indicator is defined as:

$$\bar{q}_{\text{tot}} = \frac{1}{T_{\text{sim}}} \int_0^{T_{\text{sim}}} q_{\text{tot}}(t)\ dt,$$

where T_{sim} is the total simulation duration and $q_{\text{tot}}(t) = (1/N)\sum_{i=1}^{N} q_i(t)$, in which i corresponds to each manufacturing cell, N is the total number of cells, and $q_i(t)$ is the queued volume of boxes to be transported from cell i at time t. The unit of measurement is units of wagons (considering the optimized layout).

- Total queue at the end of simulation period (q_{end}): defined as the sum of the queued quantity at the end of the simulation period. The unit of measurement is units of wagons (considering the optimized layout).

From this point, the units of measurement of the mentioned indicators will be considered as follows:

- $\bar{u}$: no unit of measurement;
- $\bar{q}_{\text{tot}}$ and q_{end}: in units of wagons[1].

Under the previously cited conditions, the model is simulated on Matlab ® and the graph of the total queued volume versus time is shown in Figure 6.1. In Appendix B.1, the Matlab ® code and a brief explanation of its logic are reported.

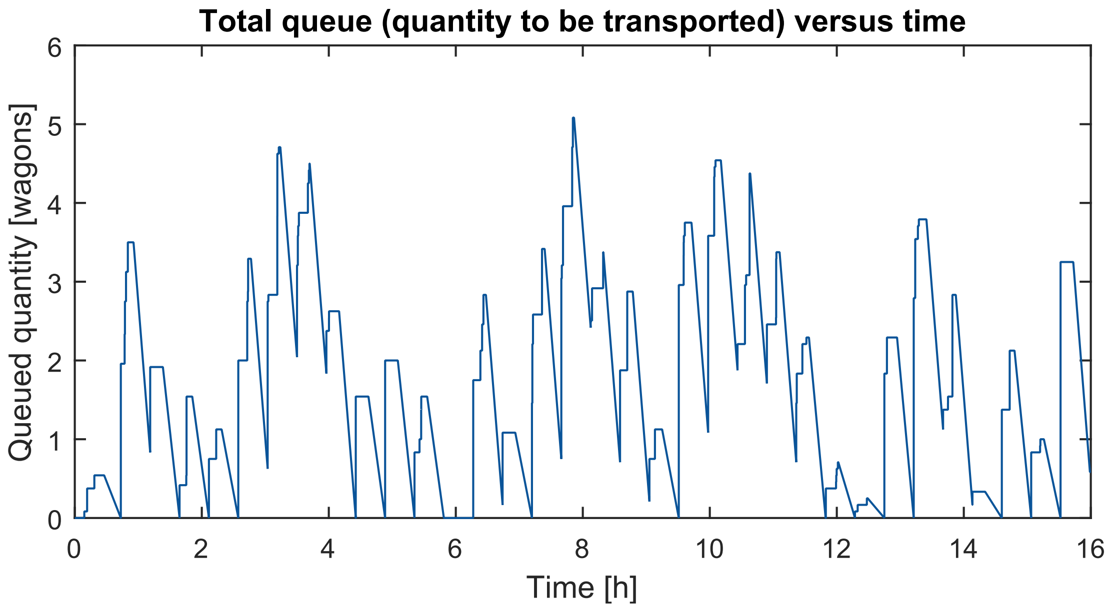


Figure 6.1: Total queued quantity to be transported versus time under the current MHS's conditions

The simulation results are:

[1]This means the fraction of a wagon's transporting capacity used to transport the referred volumes. For instance, if we consider q_{end}=0.6 wagon, it means that the referred volume corresponds to the volume of one wagon 60% saturated.

$$\bar{u} = 65.4\%,$$

$$\bar{q}_{\text{tot}} = 1.70 \text{ wagons},$$

$$q_{\text{end}} = 0.58 \text{ wagon}.$$

Note that, at the end of the simulation period, there is also a quantity of $q_{\text{end}} = 0.58$ wagon that has to be picked up on the next working day. Considering that the next day would have the same exact production volumes, and taking into account an initial queued volume of 0.58 wagon, the simulation is run again, resulting in the graph shown in Figure 6.2.

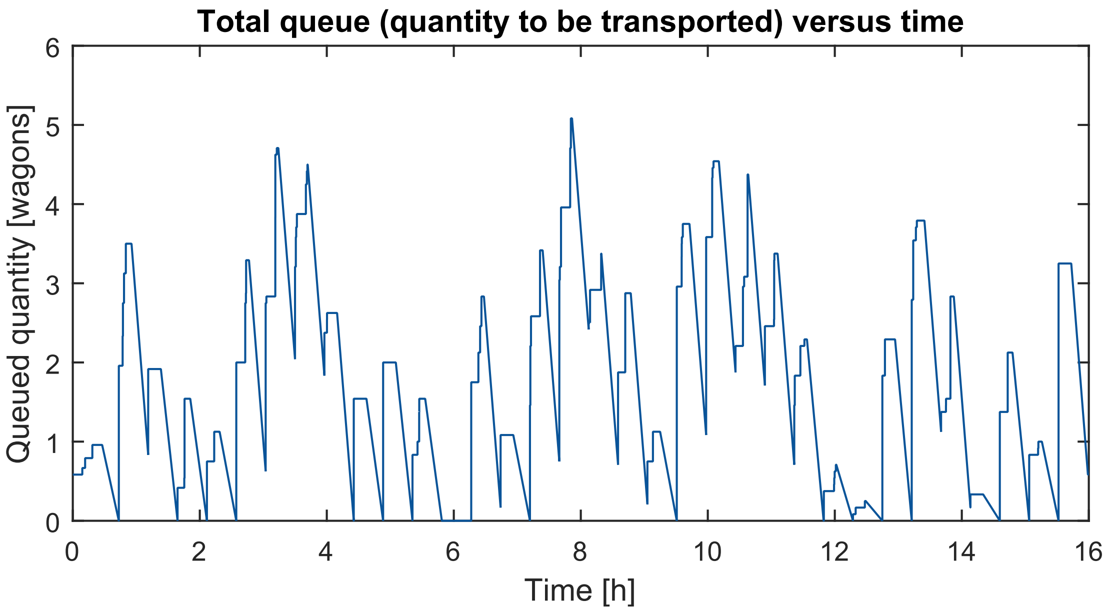


Figure 6.2: Total queued quantity to be transported versus time under the current MHS's conditions on the next working day

It is clear that the system easily absorbs the accumulated volume from the previous day. The truck is capable of picking up the accumulated quantities on its first route. The total queued volume at the end of the simulation period is the same as the day before (0.58), so it means that, if the next day would be simulated under the same conditions (same input volumes and considering the initial values accumulated from previous day), we would get the exact same curve. The resulting indicators are reported below, and these are the ones considered as the definitive ones:

$$\bar{u} = 65.8\%,$$

$$\bar{q}_{\text{tot}} = 1.72 \text{ wagons},$$

$$q_{\text{end}} = 0.58 \text{ wagons}.$$

6.2 Alternative 2 - Optimization of the current material handling system

The model applied for the optimized solution of the current MHS is practically the same utilized in the previous system. The difference is that the model is applied to each route I, II, and III, individually. In other words, the list of produced FGs is divided into the cells groups I, II, and III, and each route with a specific duration and frequency of occurrence. These values are the ones determined in Section 4.5.3 and 4.6. In addition, on this simulation, we consider that the wagons' full capacity is available for transportation. The same Matlab ® code reported in Appendix B.1 is used for this simulation.

Considering route I only, the simulation is run for the same reference day. Figure 6.3 shows the queued volume curve in time.

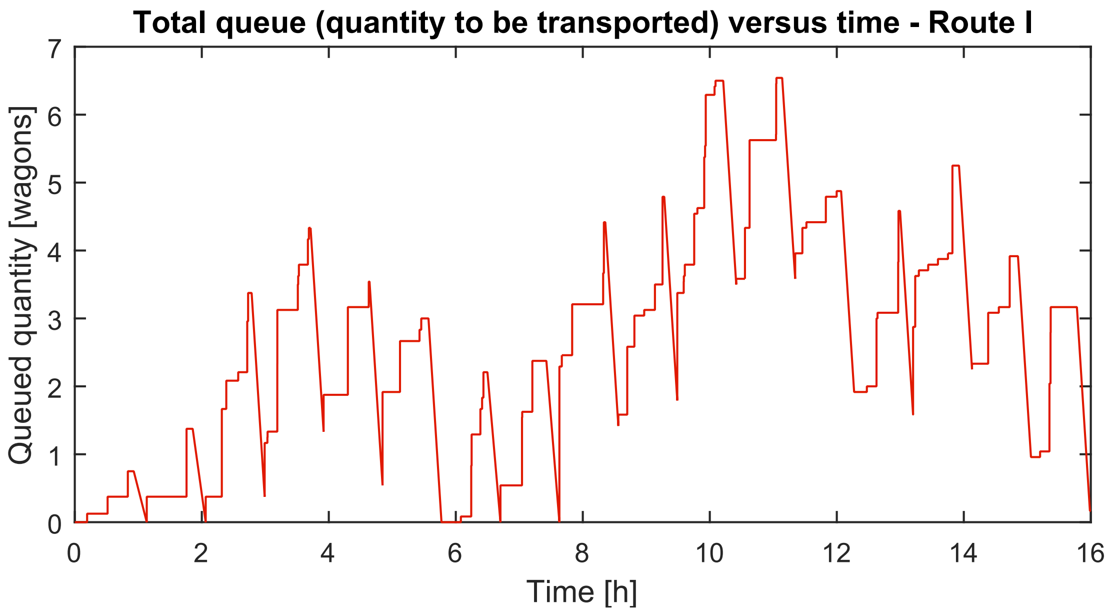


Figure 6.3: Total queued quantity to be transported versus time for the optimized solution of the current MHS - route I

Note that, again, at the end of the simulation period, there is still a $q_{\text{end}} = 0.17$ wagon to be picked up. Following the same logic explained in the previous section, another simulation is executed by taking into account the accumulated volume from the previous day. Figures 6.4, 6.5, and 6.6 show the queued volume curve for route I, II, and III, respectively. (For routes II and III, there is no residual volume at the end of the day)

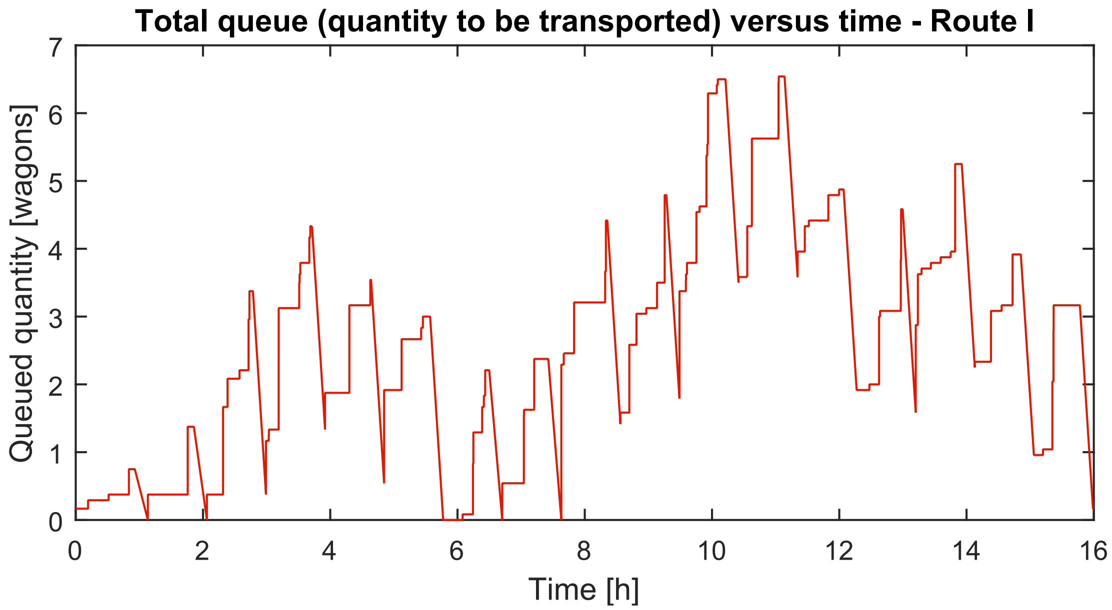


Figure 6.4: Total queued quantity to be transported versus time for the optimized solution of the current MHS, considering the accumulated volume from the previous day - route I

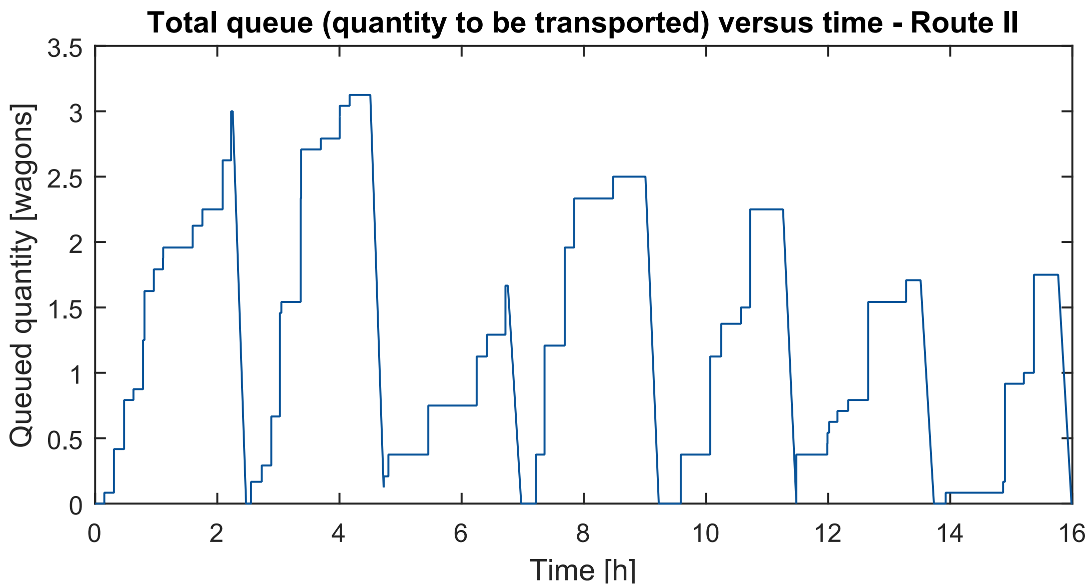


Figure 6.5: Total queued quantity to be transported versus time for the optimized solution of the current MHS - route II

The resulting indicators, individually computed by the simulations, are shown in Table 6.1.

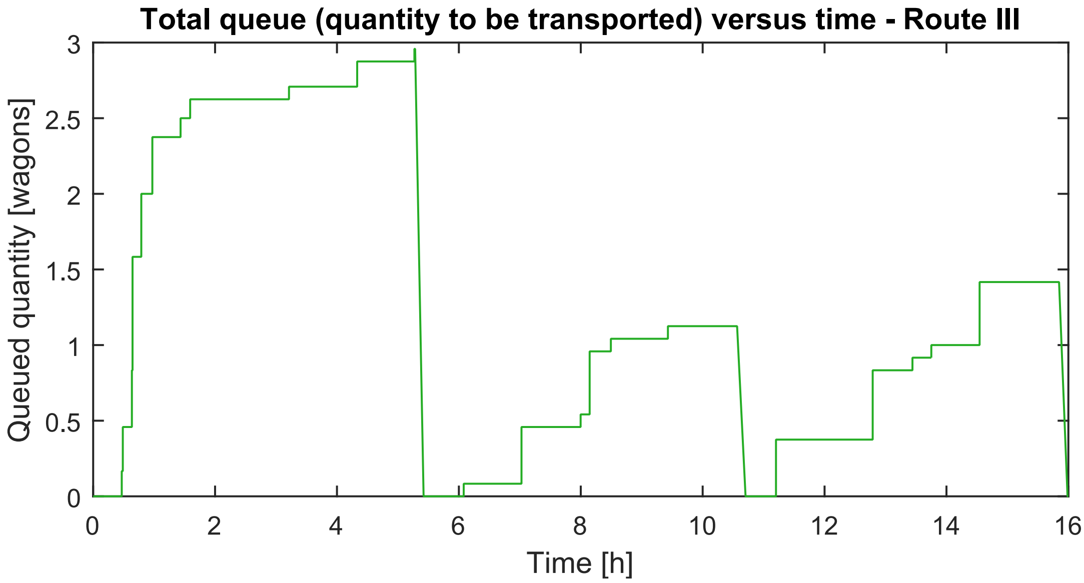


Figure 6.6: Total queued quantity to be transported versus time for the optimized solution of the current MHS - route III

Table 6.1: Indicators' resulting values for the different routes

Indicator	Route I	Route II	Route III
$\bar{u}$	89.4%	75.6%	61.1%
$\bar{q}_{\text{tot}}$ [wagons]	2.56	1.23	1.24
q_{end} [wagons]	0.17	0.00	0.00

The average global queued volume (i.e. considering the whole system) can then be calculated as

$$\bar{q}_{\text{tot}} = 2.56 + 1.23 + 1.24 = 5.03 \text{ wagons}.$$

The average global utilization can be calculated as the weighted average of the singular utilization, using the number of routes performed each day as weight:

$$\bar{u} = \frac{17 \cdot 89.4\% + 7 \cdot 75.6\% + 3 \cdot 61.1\%}{17 + 7 + 3} = 82.7\%.$$

At this point, it is already possible to compare the alterations on the MHS configurations from current system to the optimized one. Table 6.2 shows the performance indicators for both alternatives, as well as the total time spent per day by operators in the material transportation task (t_{daily}).

Note that the objective of reducing the total time spent by operators on the transporting activities (and consequently the labor cost of the activities) has been achieved In fact, the optimized system provides a 39% reduction in t_{daily}, representing a significant reduction in labor costs. This configuration also utilizes better the transporting capacity of the truck, reducing the number of routes performed

Table 6.2: Indicators' resulting values and total time spent per day in material transporting activities (t_{daily}) for alternatives 1 and 2

Indicator	Alternative 1	Alternative 2
$\bar{u}$	65.8%	82.7%
$\bar{q}_{\text{tot}}$ [wagons]	1.72	5.03
t_{daily} [min]	535.5	325.8

per day (from 34 to 27). On the other hand, the performance of the system is decreased (considering $\bar{q}_{\text{tot}}$ as performance indicator), indicating that the average queued volumes in cells would be more than doubled with respect to the current system. The impact of these results will be further discussed in Chapter 7.

6.3 Alternative 3 - Introduction of an AGV system

In order to determine the number of AGVs that would be sufficient to supply the transportation of FGs from cells to the warehouse, we conducted a simulation study. The simulation was held initially with only one AGV working in such task. This configuration is much easier to simulate because there is no possibility of traffic between vehicles, and all tasks have to be executed by the same AGV (there is no need for a task assignment analysis).

The first step in modeling this problem is to define the path through which the AGV can drive, i.e. the roads on which the magnetic tape that would be followed by the vehicle are installed. The tape can only be placed on drivable roads as indicated in Figure 4.17. Some of the drivable roads were not chosen as possible paths for the AGV because there were no pick-up points nearby.

In order to model the movement of the vehicle through the plant, the drivable roads are divided into segments defined by two consecutive nodes, as shown in Figure 6.7 in such a way that the path of the AGV between the nodes is always a straight path. A node is created when:

- there is a crossing point between different segments of the magnetic tape (e.g. node 115) - these nodes are called corner-type nodes and are shown in red;
- there is a pick-up point nearby (i.e. the output point of a cell) - these nodes are called cell-type nodes and are shown in green;
- there is a drop-off point nearby (i.e. the area within the FGWH dedicated to dropping-off the boxes from the production area) - this node is called drop-off node and is shown in yellow.

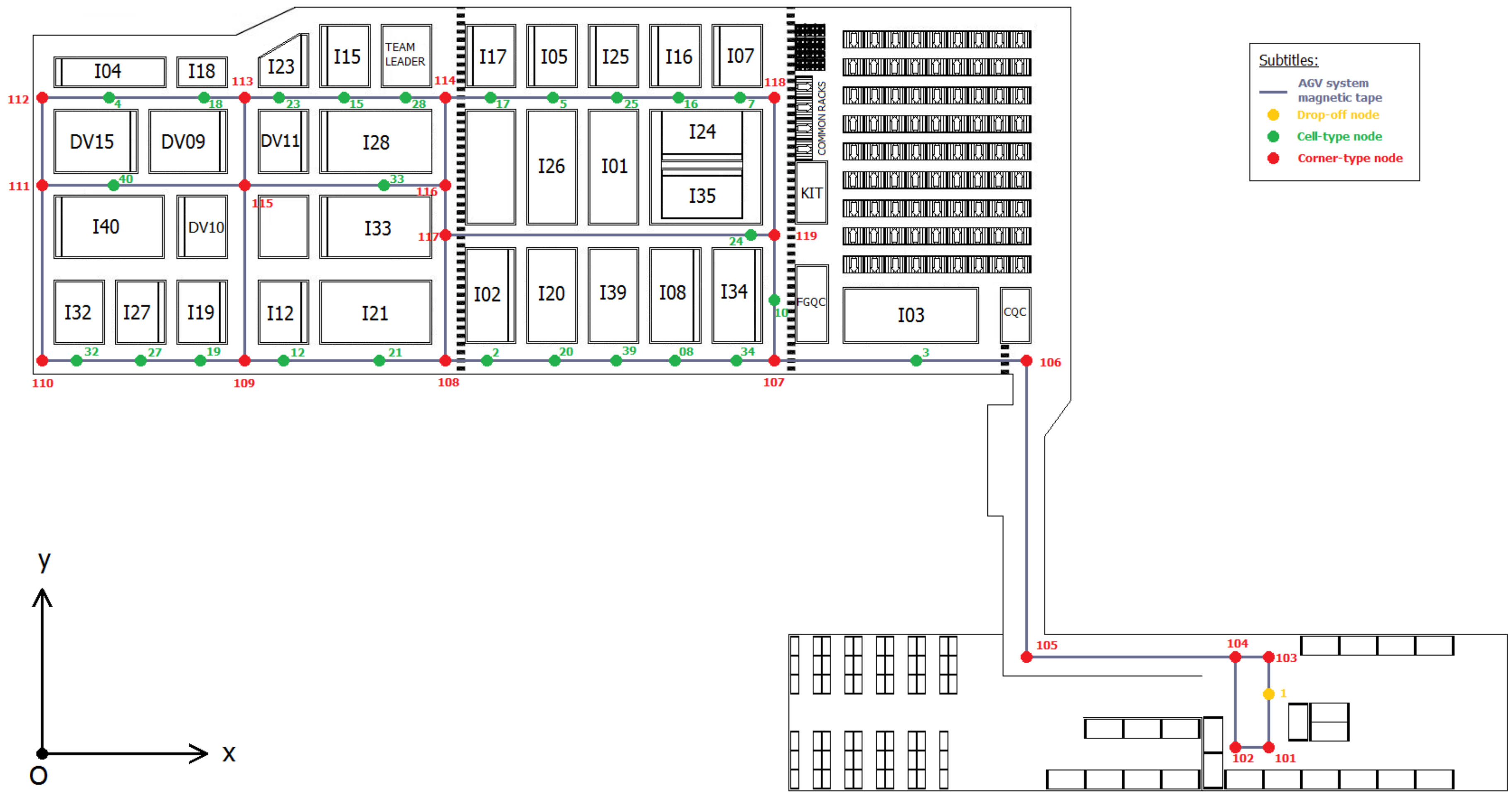


Figure 6.7: Scheme of the drivable ways for the AGV and the different nodes through the plant

The proposed model allows the distance traveled between two consecutive nodes to be calculated as a Euclidean distance between the two points. Two orthogonal axis x and y and an origin $O(0,0)$ are used as reference system as indicated in Figure 6.7. The position of each node i is then described as $(x, y)_i$ coordinates so that the distance between nodes a and b (if a and b are placed consecutively) is calculated as the Euclidean distance between them:

$$d_{a,b} = \sqrt{(x_a - x_b)^2 + (y_a - y_b)^2}.$$

Each time the AGV moves, a destination node is assigned to it. During the meetings between Indeva and Valeo, the logic employed by the AGV controlling system to determine the destination of the vehicle when boxes in more than one cell are waiting to be picked up was not revealed. So in order to simulate the behavior of the AGV, a destination choice logic had to be created. The ranking logic we propose is based on:

- giving priority to cells that are closer to the AGV - it decreases the distance traveled by the AGV and increases its efficiency (smallest distance logic);
- giving priority to cells whose boxes are waiting for a longer period of time to be picked up - it decreases the queue of boxes in a cell (longer wait logic).

A ranking parameter φ_i is attributed to each cell i according to the following expression:

$$\varphi_i = \begin{cases} 0, & \text{if no box is to be moved from cell } i, \\ \alpha \frac{\sum_j d_j}{d_i} + \beta \frac{\Delta t_i}{\sum_j \Delta t_j}, & \text{if there are boxes to be moved from cell ,} \end{cases}$$

where d_i is the Euclidean distance between the AGV and cell i and Δt_i is the time the boxes in cell i are waiting to be transported. The coefficients α and β are coefficients such that $\alpha + \beta = 1$. This way, they become tuning parameters, i.e. depending on (α, β) values, the destination assignment logic can be closer to the smallest distance logic or the longer wait one. The destination node is then chosen as the one with the highest φ_i between all the nodes.

Once the destination node is set, the challenge is to determine the smallest path through which the AGV should move from its current position and the destination. An important constraint to the determination of the path is that the AGV cannot drive backward. In other words, if the AGV comes from node $i - 1$ and arrives at node i, it cannot go back to node $i - 1$. The best way of determining the path that minimizes the distance traveled between origin and destination would be by generating all possible routes between the two nodes, calculating the distance traveled for each of them and then finding the smallest one. This calculation is quite complex and time-consuming, and it would have to be performed each time the AGV sets a new objective.

Due to the complexity of the problem, we propose a simpler algorithm that provides a possible path between origin and destination. It may not provide the shortest one depending on the origin and destination nodes, but it always provides a possible path between them.

Figure 6.8 provides a scheme of the algorithm's logic. It illustrates a hypothetical mesh with segments connected by nodes. Let us suppose that the node on which the AGV is at the moment (i), the node from which it came (p) and the destination (d) node are known. In addition, all the nodes directly connected to the current AGV node are known (a, b, c). For each of them, the Euclidean distance to the destination node is calculated (d_a, d_b, d_c). Note that the distance is not calculated for the node from which the AGV came because it cannot drive in that direction at the moment. The node to which the AGV should go is set as the one with the smallest distance to the destination node (in Figure 6.8 the chosen one would be node c). The process is repeated until the vehicle reaches the destination node. The proposed algorithm is inspired by the A* algorithm, a search strategy for finding the minimum cost path, first introduced by Hart et. al [54]. Here, the path cost is determined by the Euclidean distance between the adjacent nodes and the destination. Additionally, our algorithm eliminates the possibility of regressing to the previous node.

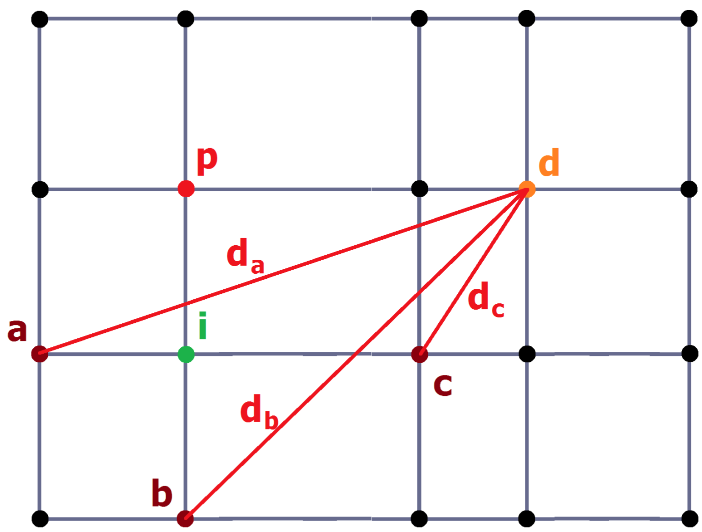


Figure 6.8: Illustration of the algorithm utilized in this thesis for determining the path through which the AGV should move from its current position to the destination

After each pick-up or drop-off activity, the AGV verifies whether there are any boxes to be picked up. If so, it verifies if there is still space in its wagons for at least one of those boxes. If positive, it calculates the ranking parameter and goes to the next cell. Otherwise, the drop-off point is set as its destination.

If there is no box to be picked up at the moment, the AGV verifies if there are any boxes in its wagons. If they are empty, it remains stopped until the next box is produced, otherwise, it goes to the drop-off point.

The problem has one particularity to be addressed. When the AGV is sent to the drop-off point, it has to stop first in the FGQC station. It is assumed that the quantity and size of boxes dropped off at that station is equal to the quantity and size of boxes picked up. This way, the quantity of material transported by the AGV remains the same after the stop. It then goes directly to the drop-off point.

The main parameters that govern the problem are the following:

- AGV's transporting capacity (q_{transp}): the available volume that the vehicle is capable of transporting.

- Tuning parameters (α and β): as discussed previously.

- AGV's average speed ($\bar{v}$): average speed of AGV while moving through the plant. This is different from the nominal speed of the vehicle. It takes into account the time it remains stopped if there is any kind of obstruction on its path, as well as acceleration and deceleration movements. In all these situations, the vehicle travels with an average speed lower than the nominal one.

- AGV's average stopped time in cells ($\bar{t}_{\mathrm{stop}}$): supposing that the AGV is loaded manually, it remains stopped while waiting for an operator to pick up the boxes and place them on the wagons. The operator is usually performing production activities, so the AGV would have to wait until the loading activity starts. $\bar{t}_{\mathrm{stop}}$ is the average time it has to wait at a cell before the loading activity starts.

- Average loading time per box ($\bar{t}_{\mathrm{load}}$): it has been assumed the same loading time for any type of box, independently of its size. The total loading time in a cell would be calculated as $\bar{t}_{\mathrm{load}}$ times the number of boxes to be picked up.

- Average unloading time ($\bar{t}_{\mathrm{unload}}$): time necessary to disconnect the wagons from the AGV and to attach empty wagons to it. If this activity is performed manually, a waiting time $\bar{t}_{\mathrm{wait}}$ is added to the total unloading time.

The simulation is held for a single day of work (considering two shifts). The input data for the simulation is a list of every box that is produced in a day and the time in which it is considered available to be transported to the warehouse. These are real data from a regular day of work. In Appendix B.2, the Matlab ® code and a brief explanation of its logic are reported.

The simulation results are reported in terms of the following indicators:

- Average utilization of the AGV's transporting capacity ($\bar{u}$): average percentage of the total available space for transporting boxes on the AGV effectively used. The indicator is singularly measured every time the AGV unloads at the warehouse; $\bar{u}$ is the average value of the singular measurements.

- Total distance traveled (d_{tot}): total distance traveled by the AGV during the period of simulation.

- Average total queue ($\bar{q}_{\text{tot}}$): the indicator is defined as:

$$\bar{q}_{\text{tot}} = \frac{1}{T_{\text{sim}}} \int_0^{T_{\text{sim}}} q_{\text{tot}}(t)\ dt,$$

  where T_{sim} is the total simulation duration and $q_{\text{tot}}(t) = \frac{1}{N}\sum_{i=1}^{N} q_i(t)$, in which i corresponds to each manufacturing cell, N is the total number of cells, and $q_i(t)$ is the queued volume of boxes to be transported from cell i at time t.

- Maximum queue at a cell (q_{max}): defined as the maximum queued volume at a cell during the duration of the simulation - the indicator is employed to evaluate whether the cells' buffer dimensions are compatible with the queued volumes waiting to be picked up by the AGV.

- Boxes' average waiting time ($\bar{t}_{\text{wait}}$): average time boxes wait on a cell until the AGV picks them up.

- Total queue at the end of the simulation period (q_{end}): defined as the sum of the queued quantity at the end of the simulation period.

It is important to emphasize that $\bar{v}$ is the average speed of the AGV. It is lower than its nominal speed (v_{nom}) because it takes into account the accelerating and decelerating movements, as well as possible obstruction of the AGV's road (it stops when it happens). For simplification purposes, we propose the following relation between the average and normal speed:

$$\bar{v} = 0.75 v_{\text{nom}}.$$

From now on, the units of measurements of the following parameters and indicators will be fixed as:

- q_{transp}, $\bar{q}_{\text{tot}}$, q_{max}, q_{end}: in units of wagons[2];

- α, β, $\bar{u}$: no unit of measurement;

- $\bar{v}$, v_{nom}: in meters per minute (m/min);

- $\bar{t}_{\text{stop}}$, $\bar{t}_{\text{load}}$, $\bar{t}_{\text{unload}}$, $\bar{t}_{\text{wait}}$: in seconds (s);

- d_{tot}: in kilometers (km).

The following sections describe a set of simulations held to evaluate the influence of the main parameters on the AGV problem. By maintaining all parameters fixed but one, which is varied between some specific values, it is possible to observe the impact of a specific variable on the simulation results.

[2]This means the fraction of a wagon's transporting capacity used to transport the referred volumes. For instance, if we consider q_{end}=0.6 wagon, it means that the referred volume corresponds to the volume of one wagon 60% saturated.

6.3.1 Influence of the tuning parameters on AGV system's performance

The simulation is executed for five different (α, β) configurations in order to evaluate the influence of the tuning parameters on the system's performance. The value assigned to each parameter is kept constant through these simulations, except α and β. Table 6.3 indicates the fixed parameters values, while Table 6.4 shows the $(\alpha,\ \beta)$ configurations for each simulation.

Table 6.3: Parameters values in simulations held to evaluate the influence of the tuning parameters on the system's performance

Parameter	**Value**
q_{transp} [wagons]	3
v_{nom} [m/min]	33.3
$\bar{v}$ [m/min]	25.0
$\bar{t}_{\text{stop}}$ [s]	50
$\bar{t}_{\text{load}}$ [s]	10
$\bar{t}_{\text{unload}}$ [s]	45

Table 6.4: Tuning parameters values for each simulation

Simulation	α	β
1	0.00	1.00
2	0.25	0.75
3	0.50	0.50
4	0.75	0.25
5	1.00	0.00

Considering the previous parameters values, Figure 6.9 shows a graph of the total queued quantity to be transported from cells versus time for five different tuning parameters values. Table 6.5 shows the indicators values for each configuration.

Table 6.5: Indicators values for different tuning parameters configurations

Indicator	**Sim.1**	**Sim.2**	**Sim.3**	**Sim.4**	**Sim.5**
$\bar{u}$	75.6%	70.7%	68.5%	68.5%	70.7%
d_{tot} [km]	16.6	16.1	15.6	15.5	15.7
$\bar{q}_{\text{tot}}$ [wagons]	1.21	0.82	0.75	0.82	0.84
q_{max} [wagons]	1.88	1.88	1.58	1.95	1.96
$\bar{t}_{\text{wait}}$ [s]	3,276	2,457	1,828	1,911	2,421
q_{end} [wagons]	2.66	2.62	1.75	1.33	2.66

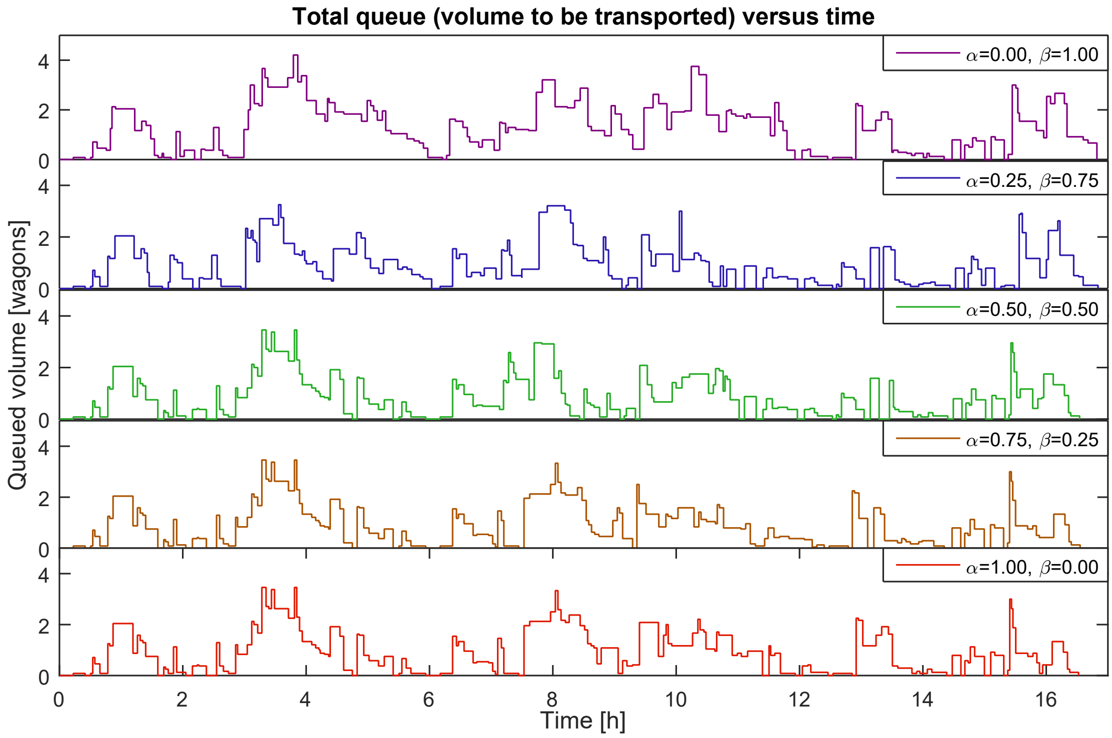


Figure 6.9: Total queued quantity to be transported versus time for different tuning parameters values

The results show that the tuning parameters have a small impact on the system's performance. $\bar{q}_{\text{tot}}$ is considered the most important indicator because it represents the system's ability to drain the volume produced by the cells - maintaining the total volume waiting to be picked up within certain limits. From this point of view, the (α, β) configuration employed in simulation 3 is the one that delivers the best performance. A purely distance related ranking logic (simulation 1) delivers the worst system performance, both in terms of average total queued volume and average waiting time. The utilization is the lowest under the scenario of simulation 3. However, having a lower utilization is not necessarily undesirable. It may indicate that the system is not working at its full capacity, i.e. if the production volumes were slightly increased, the system would still be able to meet up with the new demand.

We conclude that, among the considered tuning parameters configurations, the one that results in the best system performance is $(\alpha, \beta) = (0.5, 0.5)$.

6.3.2 Influence of the transporting capacity on AGV system's performance

The simulation is executed for four different transporting capacity configurations in order to evaluate its influence on the system's performance. The value assigned to each parameter is kept constant through these simulations, except for α and β. Table 6.6 indicates the fixed parameters values, while Table 6.7 shows the transporting capacity configurations for each simulation.

Table 6.6: Parameters values in simulations held to evaluate the influence of the transporting capacity on the system's performance

Parameter	**Value**
α	0.5
β	0.5
v_{nom} [m/min]	33.3
$\bar{v}$ [m/min]	25.0
$\bar{t}_{\text{stop}}$ [s]	50
$\bar{t}_{\text{load}}$ [s]	10
$\bar{t}_{\text{unload}}$ [s]	45

Table 6.7: Transporting capacity values for each simulation

Simulation	q_{transp} [wagons]
1	1
2	2
3	3
4	4

Considering the previous parameters values, Figure 6.10 shows a graph of the total queued quantity to be transported from cells versus time for four different transporting capacity values. Table 6.8 shows the indicators values for each configuration.

Table 6.8: Indicators values for different transporting capacity configurations

Indicator	**Sim.1**	**Sim.2**	**Sim.3**	**Sim.4**
$\bar{u}$	95.3%	86.5%	68.5%	60.9%
d_{tot} [km]	18.9	15.6	15.6	15.8
$\bar{q}_{\text{tot}}$ [wagons]	7.63	1.39	0.75	0.64
q_{max} [wagons]	4.50	1.83	1.58	1.58
$\bar{t}_{\text{wait}}$ [s]	15,601	3,526	1,828	1,107
q_{end} [wagons]	14.5	2.62	1.75	1.33

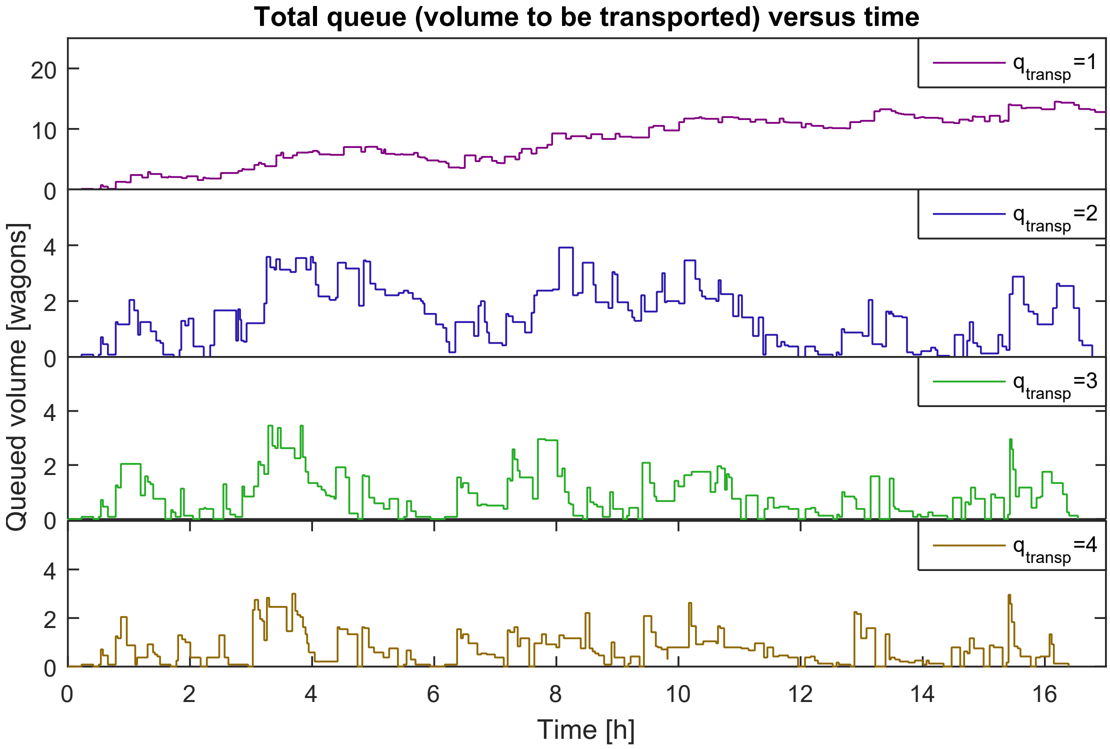


Figure 6.10: Total queued quantity to be transported versus time for different transporting capacity values

Figure 6.10 shows the high influence of the AGV's transporting capacity on the system's performance. It is clear that an AGV with one wagon capacity would not be able to drain the production volumes because the total queued volume increases with time (note that, at the end of the simulation, the total volume still to be picked up is 14.5 wagons). As q_{transp} increases, the system's performance improves (both in terms of $\bar{q}_{\text{tot}}$ and $\bar{t}_{\text{wait}}$). The decreasing utilization indicates again that the system is not working at its full capacity and thus it would work efficiently for higher production volumes.

It is clear that system performance increases with q_{transp}, so we should use the highest q_{transp} possible. It is hard to evaluate the maximum number of wagons that could be attached to the AGV considering deceleration and cornering situations without having a physical vehicle to test in on.

Indeva Tugger AGV has a maximum towing capacity of 750 kg or 1500 kg, depending on the model. Valeo's internal policy defines, as a general rule, that the maximum allowed weight of a box is 10 kg. In practice, the average weight of boxes is significantly below that value, around 6 kg. So, considering that the maximum number of boxes that fit a wagon is 24 (for type-A boxes), in the worst case scenario, the wagon could transport 144 kg. Considering that the weight of a wagon is approximately 75 kg, the maximum total weight per wagon is 219 kg. Therefore, from towing capacity point of view only, the 750 kg Tugger AGV model could transport up to three wagons attached to it, while the 1,500 kg model could tug up to six wagons.

This reasoning though does not take into account difficulties that could rise up in deceleration and cornering situations. Recall that, in Section 4.4.1, the maximum number of wagons was assessed for a speed of around 6 km/h, which is much higher than the maximum nominal speed of the AGV (50 m/min, or 3 km/h). Hence, it seems reasonable that the AGV would execute effectively cornering and deceleration activities for at least three wagons attached to it, given that it drives at an inferior speed. Therefore, we set $q_{\text{transp}} = 3$ wagons for the following simulations. Hence, it results in the choice of the 750 kg Tugger AGV as the final vehicle model.

6.3.3 Influence of the vehicle's nominal speed on AGV system's performance

The simulation is executed for four different v_{nom} (and consequently v) configurations in order to evaluate the influence of the vehicle's nominal speed on the system's performance. The value assigned to each parameter is kept constant through these simulations, except for v_{nom} (and consequently v). Table 6.9 indicates the fixed parameters values, while Table 6.10 shows the (v_{nom}, v) configurations for each simulation.

Table 6.9: Parameters values in simulations held to evaluate the influence of the vehicle's nominal speed on the system's performance

Parameter	**Value**
q_{transp} [wagons]	3
α	0.5
β	0.5
$\bar{t}_{\text{stop}}$ [s]	50
$\bar{t}_{\text{load}}$ [s]	10
$\bar{t}_{\text{unload}}$ [s]	45

Table 6.10: Vehicle's nominal and average speed values for each simulation

Simulation	v_{nom} [m/min]	v [m/min]
1	5.0	3.8
2	20.0	15.0
3	35.0	26.2
4	50.0	37.5

Considering the previous parameters values, Figure 6.11 shows a graph of the total queued quantity to be transported from cells versus time for four different speed values. Table 6.11 shows the indicators values for each configuration.

It is very clear that the nominal speed has an expressive influence on the system's performance. In fact, $\bar{q}_{\text{tot}}$ decreases rapidly with increasing nominal speed

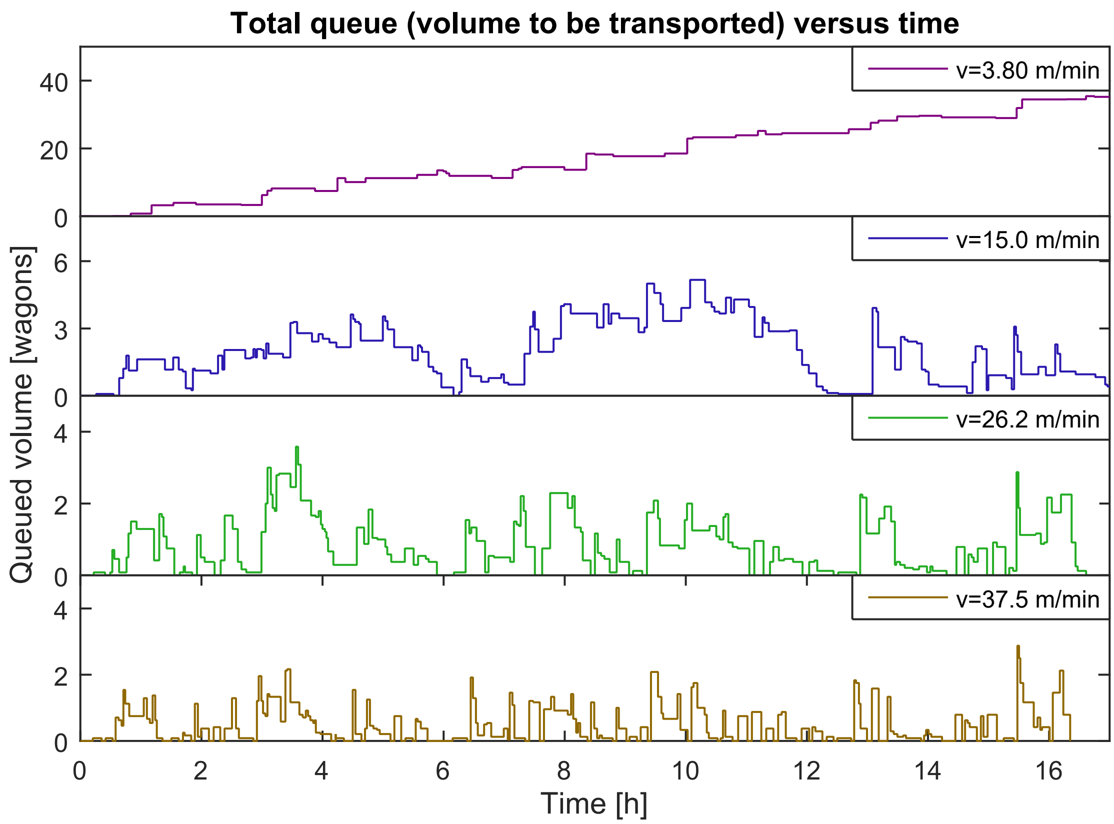


Figure 6.11: Total queued quantity to be transported versus time for different vehicle's nominal speed values

Table 6.11: Indicators' resulting values for different vehicle's nominal speed configurations.

Indicator	**Sim.1**	**Sim.2**	**Sim.3**	**Sim.4**
$\bar{u}$	97.6%	91.4%	68.5%	43.0%
d_{tot} [km]	6.9	10.7	16.3	19.6
$\bar{q}_{\text{tot}}$ [wagons]	17.21	1.87	0.79	0.43
$q_{\max}$ [wagons]	12.08	2.63	1.58	1.58
$\bar{t}_{\text{wait}}$ [s]	34,902	4,240	2,036	1,915
q_{end} [wagons]	35.2	2.29	2.17	2.12

of the AGV. Note that, for the fastest configuration, the average queued volume is very low. Additionally, utilization is quite low, indicating that the same system could perform effectively the transporting task for higher production volumes.

As the configuration employed in simulation 4 is the one that shows the best system performance, we will consider $v_{\text{nom}} = 50.0$ m/min (and $v = 37.5$ m/min) for the final AGV configuration.

6.3.4 Influence of the average stopped time on AGV system's performance

The simulation is executed for four different average stopped time configurations in order to evaluate its influence on the system's performance. The value assigned to each parameter is kept constant through these simulations, except $\bar{t}_{\text{stop}}$. Table 6.12 indicates the fixed parameters' values, while table 6.13 shows the average stopped time configuration for each simulation.

Table 6.12: Parameters values in simulations held to evaluate the influence of the average stopped time on the system's performance

Parameter	**Value**
q_{transp} [wagons]	3
α	0.5
β	0.5
v_{nom} [m/min]	50.0
$\bar{v}$ [m/min]	37.5
$\bar{t}_{\text{load}}$ [s]	10
$\bar{t}_{\text{unload}}$ [s]	45

Table 6.13: Average stopped time values for each simulation

Simulation	$\bar{t}_{\text{stop}}$ [s]
1	25
2	50
3	75
4	100

Considering the previous parameters values, Figure 6.12 shows a graph of the total queued quantity to be transported from cells versus time for four different transporting capacity values. Table 6.14 shows the indicators values for each configuration.

Table 6.14: Indicators values for different average stopped time configurations

Indicator	**Sim.1**	**Sim.2**	**Sim.3**	**Sim.4**
$\bar{u}$	37.1%	43.0%	54.8%	66.4%
d_{tot} [km]	22.4	19.6	18.4	16.4
$\bar{q}_{\text{tot}}$ [wagons]	0.33	0.43	0.57	0.71
q_{max} [wagons]	1.33	1.58	1.58	1.46
$\bar{t}_{\text{wait}}$ [s]	3,585	2,093	1,632	1,188
q_{end} [wagons]	1.33	1.75	1.75	2.12

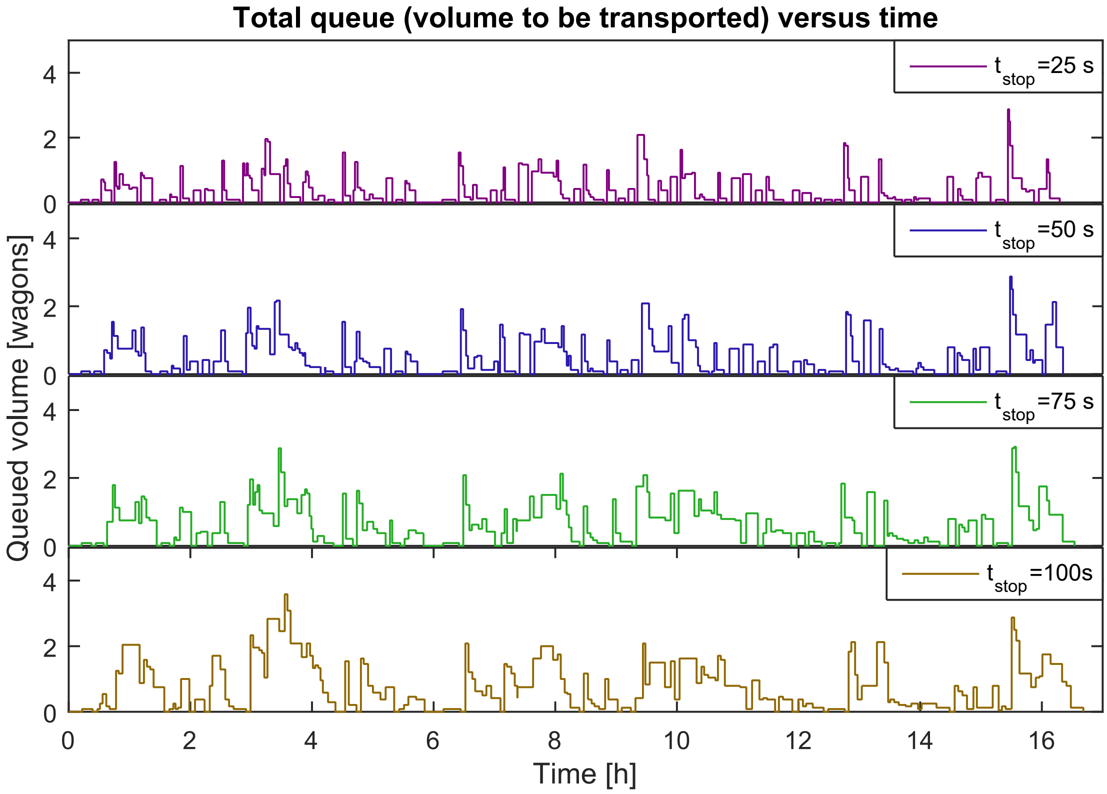


Figure 6.12: Total queued quantity to be transported versus time for different average stopped time values

For the considered configurations, it is clear that the AGV system is not working close to its full capacity - given the quite low utilization values. Note that the system is already working at the maximum nominal speed ($v_{\text{nom}} = 50$ m/min). The average stopped time though influences slightly the system's performance - in fact, $\bar{q}_{\text{tot}}$ more than doubles from simulation 1 to simulation 4.

It is important to highlight that production operators are responsible for loading the material onto the AGV, i.e. when the vehicle stops at a specific cell, one of its operators, when available, should place the boxes on the AGV's wagons. Therefore, the parameter $\bar{t}_{stop}$ is directly related to the availability of the production operators to perform the loading activity. So, by assuming a small $\bar{t}_{stop}$ value, it implies on a fast response of operators when the vehicle stops at a cell; this could be a problem for production activities that cannot be interrupted before its completion. To assume a larger $\bar{t}_{stop}$ value means to allow the response time of operators to be longer, so that abrupt interruptions in production can be avoided.

Taking into account the previously related perspective, we will assume $\bar{t}_{stop} = 100$ s for the final AGV configuration.

6.3.5 Other parameters

The influence of parameters t_{load} and t_{unload} will not be evaluated. That is because these parameters can be quite easily assessed by performing physical tests. The elements required for these tests (wagons and boxes) are available to the company, and an AGV is not required to assess these two parameters.

Considering the time estimation analysis reported in Section 4.5.2, we assume $t_{\text{load}} = 10$ s and $t_{\text{unload}} = 45$ s.

6.3.6 AGV system final configuration

Considering the analysis of the different parameters that influence the AGV system's performance, as reported in the previous sections, a final simulation is executed for the chosen parameters values as shown in Table 6.15.

Table 6.15: Final configuration of parameters' values for the AGV system simulation

Parameter	Value
q_{transp} [wagons]	3
α	0.5
β	0.5
v_{nom} [m/min]	50.0
$\bar{v}$ [m/min]	37.5
$\bar{t}_{\text{load}}$ [s]	10
$\bar{t}_{\text{unload}}$ [s]	45
$\bar{t}_{\text{stop}}$ [s]	100

The graph of the total queued quantity in cells versus time is shown in Figure 6.13, while the resulting indicators are reported in Table 6.16.

Table 6.16: Indicators' resulting values for the final parameters configuration

Indicator	Value
$\bar{u}$	66.4%
d_{tot} [wagons]	16.4
$\bar{q}_{\text{tot}}$ [wagons]	0.71
q_{max} [wagons]	1.45
$\bar{t}_{\text{wait}}$ [s]	3,585
q_{end} [wagons]	1.75

Note that, at the end of the two working shifts, there is still a total queued volume of $q_{\text{end}} = 1.75$ to be picked up by the AGV. This amount should then be picked up on the next working day, so the simulation should be performed considering an initial accumulated volume to be picked up. Another simulation is performed taking into account this initial accumulated quantity. The graph of the

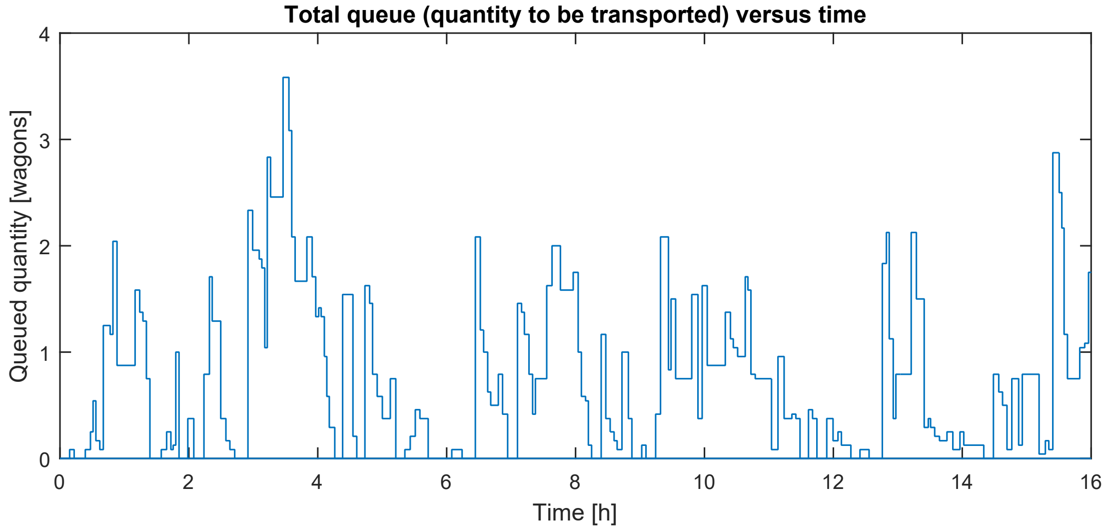


Figure 6.13: Total queued quantity to be transported versus time for the final parameters configuration

total queued volume versus time is then shown in Figure 6.14, while the resulting indicators are reported in Table 6.17.

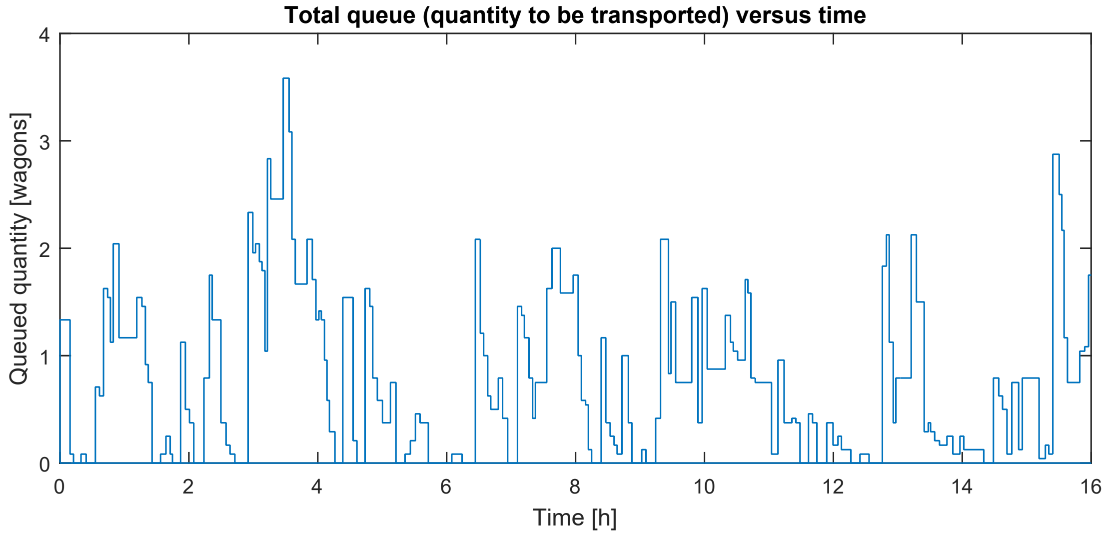


Figure 6.14: Total queued quantity to be transported versus time for the final parameters configuration, considering the accumulated volume from the previous working day

By comparing the results in Tables 6.16 and 6.17, we note that the indicators change slightly by considering the accumulated volume from the previous working day. The average queued volume increases on a small proportion, and the total queued volume at the end of the simulation period matches the one from the previous simulation. It means that the accumulated volume can be handled by

Table 6.17: Indicators' resulting values for the final parameters configuration, considering the accumulated volume from the previous working day.

Indicator	**Value**
$\bar{u}$	65.8%
d_{tot} [km]	16.4
$\bar{q}_{\text{tot}}$ [wagons]	0.74
q_{max} [wagons]	1.45
$\bar{t}_{\text{wait}}$ [s]	3,530
q_{end} [wagons]	1.75

the system during the day without compromising its performance. If the next working day was to be simulated, by adopting the same production volumes, the results would be the same as the ones shown in Table 6.17.

The results shown in Table 6.17 - that is, considering that the accumulated volumes from the previous working day are to be picked up on the current day - are be the ones taken into account for comparing the different transporting alternatives to be discussed in the next section.

Considering this AGV system configuration, 816 boxes are picked up on that specific day, from which 350 contain FGs. The AGV stopped 194 times at cells, and 34 times at the FGWH. Considering these parameters and the singular times' estimation explained in Section 5.4, we can estimate the human labor employed on the activities related to the AGV (also defined in Section 5.4). Table 6.18 reports the total estimated time spent by Valeo's operators on the AGV system activities.

Table 6.18: Total time spent per day by Valeo operators on activities related to the AGV system

Activity	**Total time**
aI	816×10 s = 136 min
aII	194×20 s = 64.7 min
aIII	350×6 s = 35.0 min
aIV	34×50 s = 28.3 min
	264.0 min

Chapter 7

Economic and financial analysis of the different material handling alternatives

The performance of each system has been evaluated through a simulation study described in the previous chapter. We now present an economic analysis of the three alternatives, as well as the profitability of a possible investment in the AGV system.

Valeo does not authorize the disclosure of internal costs (such as labor costs, values of contracts with suppliers, etc.), for confidentiality reasons. This way, the figures analyzed are not disclosed, but the resulting graphs and financial indicators are presented and analyzed.

By the time this analysis was performed, the Italian government, by means of the Ministry of Economic Development, launched a national program for encouraging innovation within the industrial environment. The so-called Industry 4.0 National Plan was created having as objective the modernization of the Italian companies' tooling and machining. This would result in a technological and digital transformation of the Italian manufacturing facilities. The incentive was established on the Italian law number 232 of December 11th, 2016. The law refers to an increase in the purchasing cost of specific goods with the purpose of deduction of amortization quotas. This results in an increase in the annual amortization quota of the asset, which is fiscally deductible [55].

The amortization of an asset (considering a good with duration of over a year) is an accounting procedure that divides its purchasing cost between its useful life [55]. The quota to be amortized in each year when a long-term asset is purchased is defined by the Italian government according to two factors: the business sector of the purchasing company, and the category to which the good belongs [56].

According to the official document "Amortizing coefficient of the cost of instrumental material goods used on commercial, artistic and professional activity" (from January 1st, 1989) [57], released by the Italian Ministry of Finance, Valeo's plant in Santena would fit into the Group 7 - Mechanical and metallurgical manufacturing industry. More specifically, it would belong to the Species XVII - Manufacturing of vehicles and chassis, as well as spare parts and accessories.

The category to which the AGV would belong is the following: motorized vehicle for transportation (heavy vehicles in general, forklifts, internal transportation vehicles, etc.). For this product category and the previously cited company classification, the correspondent amortization coefficient is 20%. This means that the total cost of the good is to be amortized over five years with equal quotas of 20% each year.

The Industry 4.0 National Plan has two programs, the so-called Super Amortization and Hyper Amortization plans. The first one, enacted in 2016, grants the company that buys a new instrumental good the increase of 40% of its purchasing cost in the declaration of expenses of the company. The second one, on the other hand, offers a 150% increase in its declared purchasing cost. Note that the company pays the Italian Company Income Tax (IRES), a proportional tax whose quota, by the time this thesis was written, was 24% [58]. The purchasing of instrumental goods implies on the deduction of this tax (to be amortized over some years). This way, by considering an increase in the declared purchasing price, the company is granted a higher deductible tax amount.

The choice between the two programs depends on some characteristics of the good. The Super Amortization plan is applicable to any instrumental good. An instrumental good can be defined as the one that has a long duration use and is applied as an instrument within the production process of the company [55]. The Hyper Amortization plan, on the other hand, is more stringent: it requires that the good is interconnected to the company's production control system or to the supply chain [55].

In practice, a regular good would have a 24% deductible amount on the purchasing price (to be amortized over a predefined period). If the good fits the requirements of the Super Amortization plan, it would have a tax deduction amount of 33.6%. Finally, if it can be fitted into the Hyper Amortization plan, the deductible tax amount reaches 60%.

Indeva informed Valeo that the AGV sold individually fulfills the requirements of the Super Amortization plan. If the supervisor and controller module is purchased (as described in Section 5.2), the new configuration is able to fit the Hyper Amortization plan, due to its interconnectivity characteristic.

As defined in Section 6.3.6, for the predefined tasks to be performed by the AGV, a single vehicle is capable of performing effectively these tasks. The purchasing of a supervisor module becomes more important with the increase in the quantity of AGVs, coordinating the movements by taking into account the precise position of each vehicle on the plant. Although it may seem unnecessary at this point, due to the significant increase in the fiscal incentive for interconnected solutions, the profitability analysis of the AGV system implementation will be performed taking into account two different configurations: the first one without the supervisor unit, and the second one including this module. The capabilities of the supervisor would be only partially used at first, however, if Valeo would like to increase its AGV fleet in the future (due to an increase in production volumes, or to the addition of new tasks to be performed by the AGVs), it would yet be prepared for an interconnected system.

In this section, the different MHSs will be analyzed from the economic and financial perspective. The four different alternatives that will be analyzed are the following:

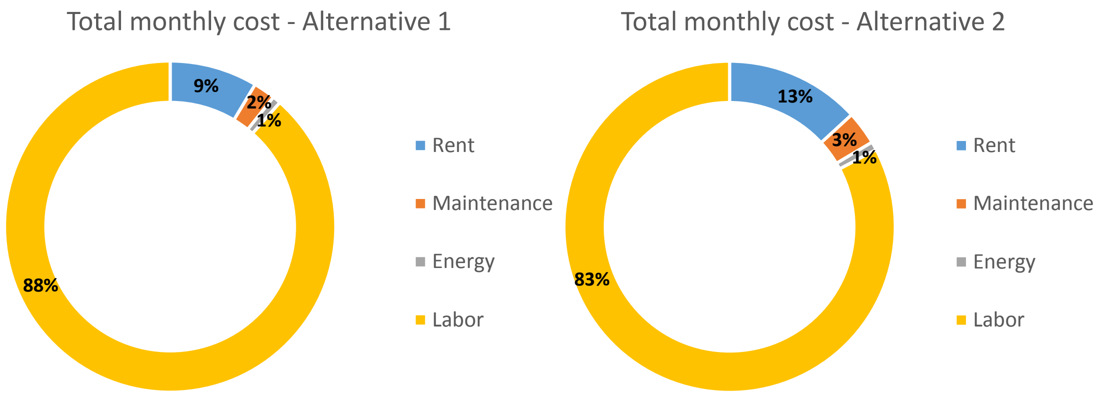
- Alternative 1: the current MHS (as described in Chapter 3);
- Alternative 2: the optimized solution of the current MHS (as described in Chapter 4);
- Alternative 3: the AGV system (as described in Chapter 5) without the supervisor module;
- Alternative 4: the AGV system (as described in Chapter 5) with the supervisor module.

The first characteristic to be analyzed is the monthly cost of each system alternative. The towing truck that is currently used by the company is rented by Toyota Material Handling, in a contract that includes the use of the equipment and its maintenance (we consider here that 80% of the contract amount refers to the use of the truck and 20% to its maintenance). For each alternative, four cost categories are determined: rent cost (if applied), maintenance cost, energy cost and labor cost. These cost components are calculated according to the logic that follows:

- Rent cost: defined by contract.
- Maintenance cost: defined by contract.
- Energy cost: it takes into account the capacity of the vehicle's battery (provided by the suppliers in Appendices A.1 and A.3), the expected duration of the battery (estimated for towing truck, and defined in Appendix A.3 for AGV) and the average cost of energy for Italian companies [59].
- Labor cost: defined as the total time spent by Valeo's operators on activities directly related to those performed by the MHS, times a cost hourly rate. This rate, provided by Valeo upon a confidentiality agreement, takes into account the total hourly cost of an operator, i.e. all the costs directly and indirectly related to the worker (wages, training, insurance, transportation, etc.).

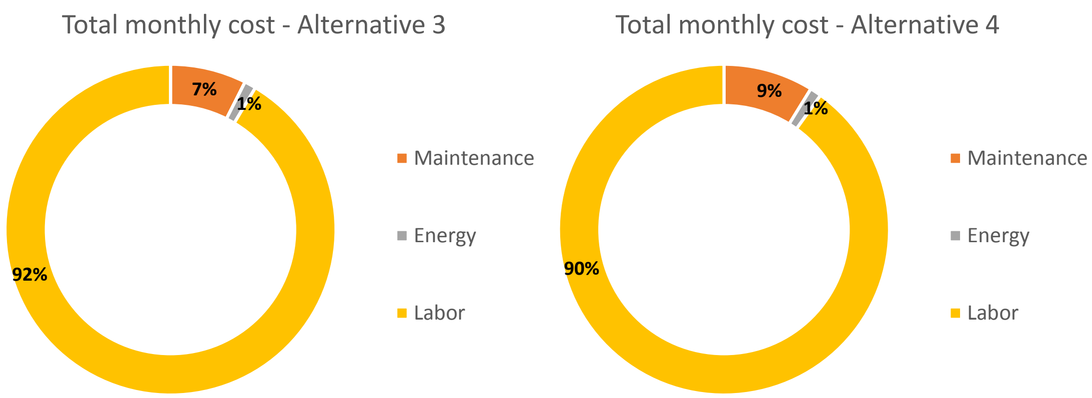
Figure 7.1 shows the different components of the monthly cost of alternatives 1 and 2, which present a quite similar cost structure. The rent and maintenance figures are the same, and the cost of energy in alternative 2 is slightly reduced (although this fraction is almost insignificant if compared to other cost components). The largest difference is perceptible on the labor cost, which is significantly reduced in alternative 2.

Figure 7.2 shows the results of the same cost analysis regarding alternatives 3 and 4. Again, they present a similar cost structure: the labor cost is exactly the same for both and energy consumption is practically the same, while maintenance costs are higher for alternative 4.



(a) Alternative 1 (b) Alternative 2

Figure 7.1: Cost structure of the total monthly cost for alternatives 1 and 2



(a) Alternative 3 (b) Alternative 4

Figure 7.2: Cost structure of the total monthly cost for alternatives 3 and 4

Table 7.1: Singular weight of each cost component for the four different MHS alternatives

Cost component	**Alt.1**	**Alt.2**	**Alt.3**	**Alt.4**
Rent	9%	13%	0%	0%
Maintenance	2%	3%	7%	9%
Energy	1%	1%	1%	1%
Rent	88%	83%	92%	90%

The singular weight of the different cost components is summarized in Table 7.1.

Figure 7.3 makes possible to compare the different system alternatives in terms of the magnitude of the total monthly cost.[1] Note that the objective of the optimized solution, which was to reduce the total cost of the activity, was achieved. In fact, with respect to the current situation, alternative 2 would achieve a cost

[1]For confidentiality reasons, the vertical axis in Figures 7.3, 7.4, 7.5, and 7.6 is omitted.

reduction of 34.9%, achieved mainly because of the reduction of the total time spent by operators on the material handling activity. Both AGV system solutions also provide an additional cost reduction in the total monthly cost of the activity. With respect to the current MHS, alternative 3 provides a 54.8% reduction in the total monthly cost, while alternative 4 provides 54.2%. The slight increase in total cost from alternative 3 to 4 is explained by the higher maintenance cost due to the supervisor unit (it corresponds to an increase of 1.2% with respect to alternative 3).

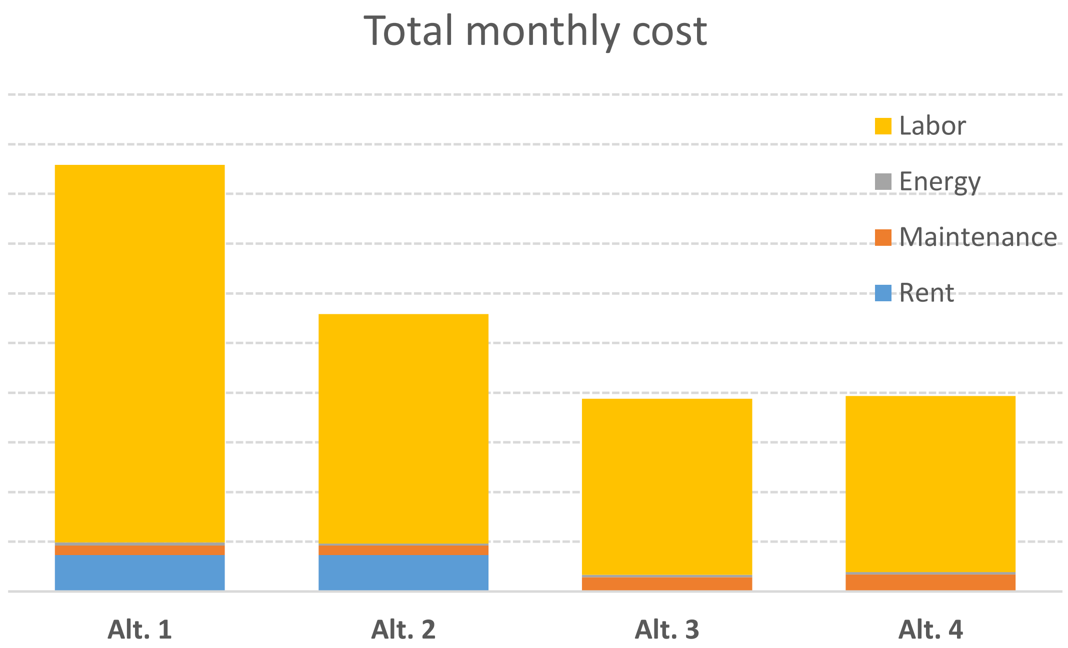


Figure 7.3: Total monthly cost directly related to the material handling activities for the different system alternatives

From the data illustrated in Figure 7.3, it is clear that alternatives 2, 3, and 4 represent a significant reduction in the total monthly cost of the studied activities. At this point, we have to evaluate the profitability of the investment if the AGVs solutions (alternatives 3 and 4) are implemented.

The main components of the total investment in the purchasing of the AGV system are the following: the price of the AGV itself, a spare battery, a battery support (to be installed on the vehicle), the guiding magnetic tape, the Kanban system, the supervisor unit and the installation service. The fraction of the total investment correspondent to each of the previous components are illustrated in Figure 7.4. Note that the difference between the investment of alternatives 3 and 4 are due to the introduction of the supervisor unit.

Two indicators are used to evaluate the profitability of the investment in an AGV system: the discounted payback period (DPBP) and the discounted net present value (DNPV). We assume a discount rate $r = 6.6\%$, which is the estimated cost of capital for the automotive sector in Europe according to a study of the University of New York [60]. Since the amortization of the asset is to be

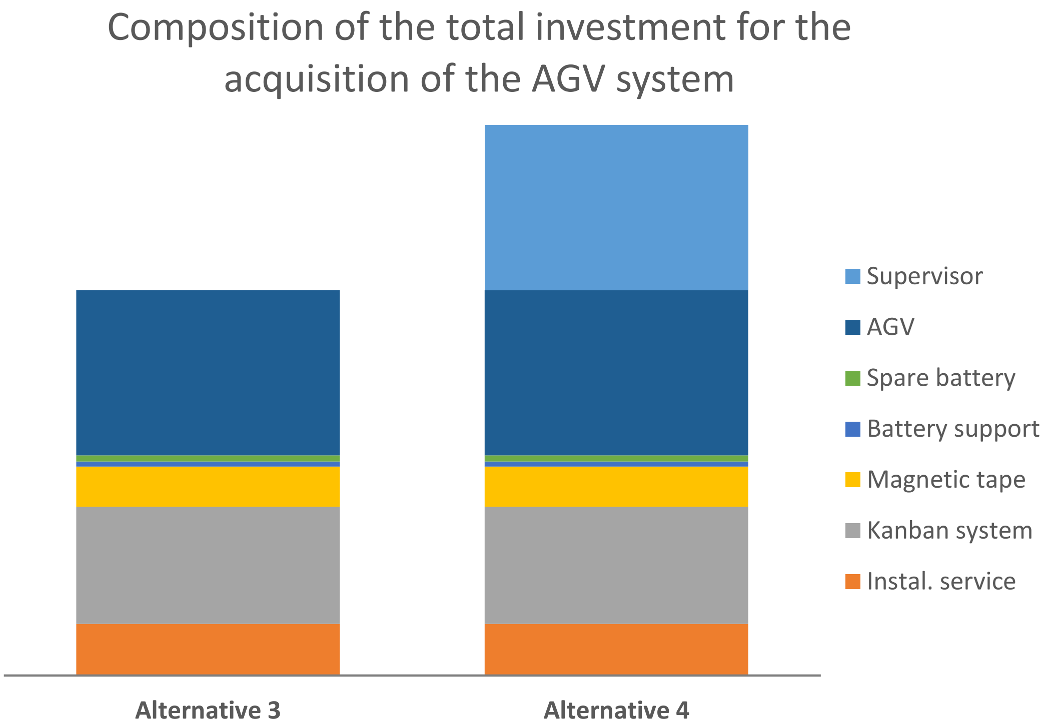


Figure 7.4: Composition of the investment required to the acquisition of the AGV system for alternatives 3 and 4 (the vertical axis represents the monetary value of the initial investment)

performed in five years according to the Italian legislation, we will consider the DNPV over the same period of operation.

Figure 7.5 shows the discounted annual impact on the Operating Result of the company due to the investment in the AGV system. The graph considers that the total investment is made in the year 2017, and the operation of the new system starts in 2018. The impact on the Operating Result is a sum of the following factors: the investment in the new system, reduction in total monthly cost respect to the current MHS, and the tax deduction due to the amortization of the asset (including the incentives of the Industry 4.0 National Plan).

Figure 7.6 shows the accumulated annual impact on the Operating Result. The graph provides a better visual comprehension of the profitability of the investment and how the financial scenario evolves in time.

For confidentiality reasons, the DNPV figure is not disclosed in this thesis. But, in order to evaluate the profitability of the investment, the DNPV is represented as a percentage of the net cost of the investment (NCI) and the initial investment (I_0). The NCI is calculated as the difference between the initial investment and the total deductible tax. On the other hand, I_0 represents the purchasing price of the AGV system. Table 7.2 shows the profitability indicators of the investments for alternatives 3 and 4. Note that DNPV is calculated over the first five years of operation.

Both ratios indicated in Table 7.2 are important and represent different aspects

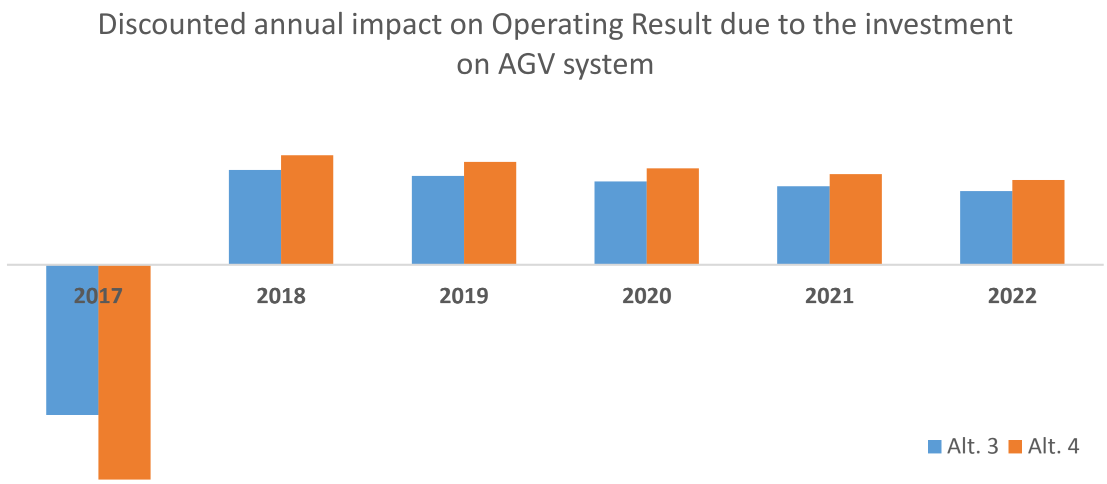


Figure 7.5: Discounted annual impact on the Operating Result of the company due to the acquisition of the AGV system - comparison between alternatives 3 and 4 (the vertical axis represents the monetary value of the annual impact on the operating result)

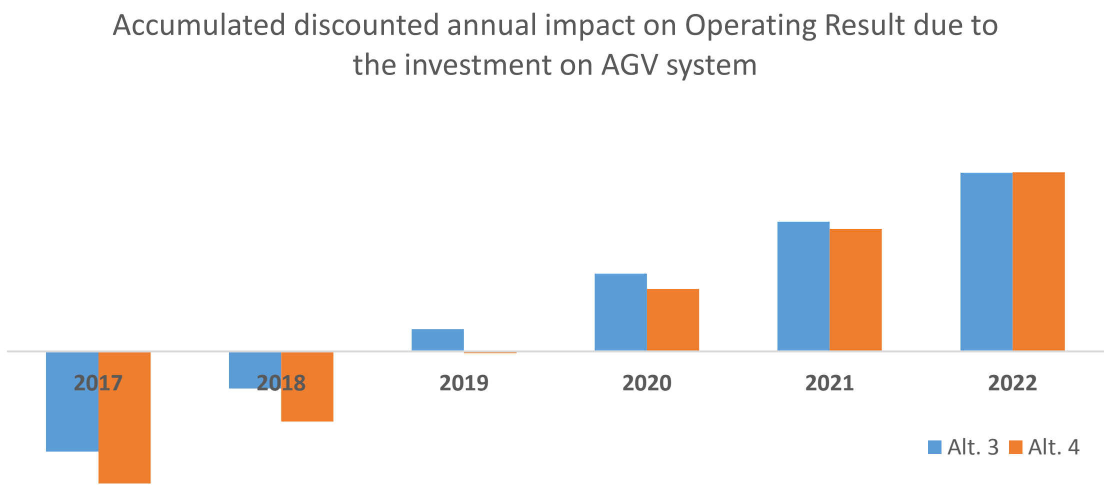


Figure 7.6: Accumulated discounted annual impact on the Operating Result of the company due to the acquisition of the AGV system - comparison between alternatives 3 and 4 (the vertical axis represents the monetary value of the accumulated impact on the operating result)

of the investment. The ratio DNPV/NCI is an economic measurement of the investment because it identifies the gain on the effective cost of the investment (here defined as NCI), which subtracts the tax deduction from the initial investment. The NCI is the net amount the company would, in fact, pay for the equipment. The DNPV/I_0 ratio, on the other hand, refers to the initial investment required. Even if the tax deductions may represent a large percentage of the initial investment, the company would receive the deductible amounts in a long period (five years). Therefore, the company has to have a cash-flow situation compatible with

Table 7.2: Financial indicators for the assessment of the profitability of the investment in the AGV system

Indicator	**Alt.3**	**Alt.4**
DPBP [years]	1.62	2.03
DNPV/NCI	269%	313%
DNPV/I_0	168%	118%

the initial investment at the moment of the purchase, because the total purchasing price is to be paid in a short period of time.

7.1 Financial and performance-based analysis of the different material handling alternatives

The final step in the analysis explored in this thesis is the definition of the best choice the company should make in terms of its MHS for the studied activities. The current situation has been described and three different systems have been analyzed so that to provide the company different alternatives. The one that suits best Valeo's objectives should then be the one selected. The purpose of this section is to summarize the performance and economic aspects involved in each alternative, highlighting the pros and cons of each of them.

The performance of the different MHS alternatives has been assessed according to the proposed models, as explored in Chapter 6. Table 7.3 summarizes the main results of the performance analysis. Note that the parameter t_{daily} is the daily total time spent by operators on the activities directly related to the different MHSs (values are expressed in minutes). Recall that alternatives 1, 2, 3, and 4 are, respectively, the current MHS, the optimization of the current system, the AGV solution without a supervisor module, and the AGV system with a supervisor module.

Table 7.3: Performance indicators for the different system alternatives

Indicator	**Alt.1**	**Alt.2**	**Alt.3**	**Alt.4**
$\bar{q}_{\text{tot}}$	1.72	5.03	0.74	0.74
u	65.8%	82.7%	65.8%	65.8%
t_{daily}	535.5	325.8	249.8	249.8

Table 7.4 shows the monthly cost reduction due to the implementation of each system alternative with respect to the current situation, as discussed in Chapter 7.

Finally, Table 7.5 shows the profitability indicators of the investment in an AGV system (alternatives 3 and 4), as discussed in Chapter 7.

Tables 7.3, 7.4, and 7.5 provide the most important parameters for the selection between the different systems. It is possible to conclude that the objective

Table 7.4: Monthly cost reduction of the different system alternatives with respect to the current system

	Alt.2	**Alt.3**	**Alt.4**
Monthly cost reduction with respect to current system	−34.9%	−54.8%	−54.2%

Table 7.5: Financial indicators for the assessment of the profitability of the investment in the AGV system

Indicator	**Alt.3**	**Alt.4**
DPBP [years]	1.62	2.03
DNPV/NCI	269%	313%
DNPV/I_0	168%	118%

of alternative 2, which was to reduce the total cost of the studied activities, is achieved. It provides a substantial cost reduction without the need for any investments in a new material handling equipment. The downside of the solution is the increase in the $\bar{q}_{\text{tot}}$ parameter. In fact, the strategy of cost reduction was to set the frequency of the pickup routes so that the production volumes between two subsequent routes would match the train capacity, avoiding unnecessary routes. It was inevitable that the average queued volume in cells would rise with respect to the current system configuration.

Both AGV solutions provide an expressive reduction in the monthly cost of the studied activities. Unlike alternative 2, the AGV solutions, while reducing the operational cost, increase substantially the system's performance (indicated by the average queued volume in cells - $\bar{q}_{\text{tot}}$). Also, the cost reduction allowed by the AGV solutions are even higher than the one provided by alternative 2. In addition, as proven in Section 6.3, the system can effectively work for slightly larger production volumes, as indicates the quite low average utilization of its transporting capacity. The profitability of the investment required for both alternatives is quite good. The payback period of both alternatives (one year and seven months for alternative 3, and two years for alternative 4) is considered acceptable for this kind of investment, and the return on the invested capital after five years of operation is very expressive.

It is important to highlight that the economic advantage of the AGV solutions over alternatives 1 and 2 is quite large not only because of the facilities promoted by the AGV system itself. A factor that impacted significantly on the labor cost reduction was the introduction of the new labeling system. In addition, the financial incentives promoted by the Italian government increases considerably the profitability of investments in these technologies at this time. However, the most significant driver of the studied activities' operational cost reduction is the AGV system and the lack of necessity for a driver to control it.

The choice between alternatives 3 and 4 relies on the company's strategical plan for the future. Alternative 4 provides a better return on the net cost of the investment. It also configures the manufacturing plant for a future increase in the AGV system's fleet. There are other material handling activities that could in the future be handled by AGVs, such the transportation of components from the receiving area to the cells. Another reason for enlarging the AGV fleet size could be an increase in the production levels of the plant. Alternative 4, though, requires a larger initial investment with respect to alternative 3.

Finally, we conclude that both AGV solutions provide a significant improvement on system performance and, at the same time, reduces its operational cost.

We suggest that the company chooses alternative 4 (AGV with a supervisor and controller unit), this way Valeo would be already structured for a future increase in the AGV fleet size. The automation of industrial and logistic processes, as discussed in Section 1.2, has a global tendency to increase, and the supervisor module could provide Valeo with a powerful tool for increasing the Santena plant's automation level. Additionally, the Hyper Amortization plan, launched by the Italian government, represents an opportunity of acquiring this technology for a much better price, and it is quite difficult to estimate for how long this program will be available. The final choice between the two alternatives, however, will be made by the company according to its strategical plan for the future.

Chapter 8

Conclusion

The scope of this thesis is to analyze the MHS employed in Valeo Santena's plant for the transportation of goods from workcells, identify possible problems, and to propose alternative configurations for enhancing the service level and reducing the operational cost. A deep analysis of the material handling equipment currently employed has been performed, as well as a full explanation of the internal material flows within the plant. The particularities of the production system, arising from the characteristics of the company's products and client profile, have also been discussed because they strongly influence the MHS constraints and requests. The same particularities also motivate the company's choice for cellular manufacturing as its production system.

The current MHS has shown to be ineffective: although it may provide a good service level, pickup routes are usually performed more frequently than necessary, and the operators pass by all workcells even if many of them would not have yet produced any package to be picked up. This implies in unnecessary labor costs since the total time employed by Valeo's operators on the transporting tasks is high. Motivated by the labor cost problem, a remodeling of the current MHS configuration has been proposed in such a way that the related labor costs are reduced. The workcells were divided into 3 groups according to the cells' individual production volumes. Each group is served by the towing truck system with a fixed route frequency, allowing for a better utilization of the truck's transporting capacity and a reduction in the total distance traveled. Based on a proposed time estimation methodology, it has been shown that the proposed modification in the MHS configuration allowed for a reduction of approximately 35% in the operational cost. Additionally, this solution does not require any investments for its implementation. The disadvantage of the proposed modification is the increase in the average queued volumes in workcells, thus reducing the performance. Also, if the production volumes of individual cells are significantly altered, the study should be performed once again (by redefining the groups of cells and the frequency of routing) to avoid a further decrease in performance.

The labor cost reduction objective has been achieved by the proposed modification, but the system's performance has been significantly reduced. This motivated the search for a solution that would allow for an operational cost reduction while maintaining or even enhancing performance. The implementation of an AGV system has been proposed and analyzed. In order to avoid a large modification in the plant layout, the selected AGV configuration does not provide a full automation of the transporting system, thus human assistance is required (for loading and unloading of materials). In 2017, when this analysis was made, the Italian government offered to industrial companies incentives for investments in automation systems, increasing tax deductions for specific equipment. This made the investment in AGV systems even more attractive at that point and represented an opportunity to acquire a supervisor unit at a much lower cost. This module would provide the company with a system easily scalable, which could be very attractive if the company decides to add other activities to the AGV work and increase the vehicles fleet size. Both AGV solutions (without or with the supervisor unit) allow for a significant cost reduction with respect to the current MHS (approximately 55%) while providing an expressive increase in service level by reducing the average total queued volume by more than 50%. They also provide flexibility to the production system, because their path can be easily altered if cells are introduced or repositioned. As discussed in Chapter 5, the AGV system, if implemented, would not be working at its full capacity, i.e. if the production volumes were slightly increased, the system would still be able to meet up with the new demand.

Although we propose that Valeo acquires the AGV solution including the supervisor unit, the final choice between the two AGV alternative configurations is to be made by the company according to its financial and strategical plan.

8.1 Advantages provided by the study to Valeo

The study reported in this thesis aimed at providing the company with a full analysis of its internal material transporting activities. The development of the work helped Valeo to understand and to document all internal material flows (from components arriving from suppliers in the receiving area, to FGs in the shipping area to be delivered to clients), the different packaging materials, the towing truck operator's activities, the basic workcell layout, etc. This work can be used to train new employees about the functioning of the in-plant logistics as well as to support managers with information for making decisions regarding the plant's internal logistics. The thesis also detected some criticalities related to the production outflow performed by a towing truck, and an opportunity of reducing labor costs directly associated to the activity was proposed. The analysis also provided the company with information that motivated the implementation study for an AGV system. The proposed model, as previously discussed, would provide Valeo with a solution capable of both reducing the operational cost and increasing system performance. The investment in this technology would be paid back by operational cost reductions and tax deductions in about two years, which is considered to be a good financial indicator in the automotive market.

8.2 Limitations of the study

The limitations of the developed study are listed as follows.

- There is no accurate information on the component's packaging material (both in terms of the type of package and the number of units per package). Hence, the volumes of components empty packages that have to be returned to suppliers had to be estimated based on observations of the arriving wagons after the towing truck routes.

- The optimization of the current system (following a strategy of labor cost reduction) was based on average values of the production volumes. The variability of production volumes has not been assessed, as well as the impact of larger production volumes on the system's performance.

- The AGV system's performance was simulated for a single day of work, due to the limitation of data collection, as described in Chapter 6. The robustness of the analysis could be enhanced if the system would be tested for multiple workdays.

- The dispatching rules according to which the AGV operates were not disclosed by the manufacturer (Indeva). Hence, a simple model had to be developed as an estimation of the vehicle's movements through the plant.

- The study was finished before the implementation of the AGV system on the plant (if Valeo chooses to do so). For this reason, it was not possible to assess the real system's performance. If the AGV system is implemented, it is suggested to measure performance and compare it to the theoretical, estimated one.

8.3 Future research

The first step Valeo should undertake after receiving this study is to actually implement the proposed AGV system. This way, it could assess the benefits highlighted by the study by measuring the system's performance and the operational costs.

The AGV system possibly implemented by Valeo could have an even higher effectiveness if some devices are added and certain procedures are adopted. As mentioned in Chapter 5, the proposed AGV system seeks to have a low impact on the current plant layout, avoiding the need for a relayout of cells disposition. A source of inefficiency on the proposed AGV solution is the fact that the system depends on human action to place the packages on its wagons. Therefore, the vehicle is obliged to remain stopped at a cell until an operator executes the material transfer task. Recall that we estimated a 100-second waiting time for each pickup. This time could be eliminated by adopting an automatic loading system. Indeva offers a gravity flow rack that can be altered in order to unload material on the AGV, with a mechanism based on a lever that is actuated by a hook on the vehicle. When the lever is moved, the rack releases the material, which slides to the vehicle's wagon. This solution also requires the AGV's wagons to be adapted. Additionally, RFID tags could replace the current labels attached to the boxes. If an RFID receiver would be installed on the gravity flow rack that receives the incoming boxes from the production area, the FGs tags could be automatically scanned.

This solution would increase the initial investment and it would have a large impact on the plant layout because all gravity flow racks used as buffering area for finished products would have to be replaced by special ones. On the other hand, it would provide a full automation of this process, reducing the labor cost directly related to the AGV system to practically zero. A new configuration can be eventually studied by the performance and economic viewpoint, evaluating whether the labor cost reduction compensates the initial investment increase.

Appendix A

Technical specifications of material handling equipment

A.1 Toyota's towing truck TSE150-708

Table A.1: Toyota's towing truck model TSE150-708's technical specification [51]

Parameter	**Unit of measurement**	**Value**
Manufacturer	-	Toyota
Model	-	TSE150-708
Drive	-	Electric
Operator type	-	Stand on
Load capacity (Q)	kg	$1,500$
Rated drawbar pull (F)	N	600
Wheelbase (y)	mm	815
Service weight including battery	kg	430
Wheel size, front	mm	250 x 80
Wheel size, rear	mm	200 x 50
Overall height (h_{15})	mm	1358
Stand height (h_7)	mm	70
Coupling height - towing pin (h_{10})	mm	199, 344
Overall length (l_1)	mm	1333
Overall width (b_1/b_2)	mm	595/584
Ground clearance, centre of wheelbase (m_2)	mm	33
Turning radius (w_a)	mm	1085

Table A.1 - continued from the previous page

Parameter	**Unit of measurement**	**Value**
Clear with driver compartment entrance (l_{24})	mm	401
Travel speed, with/without load	km/h	6.0/12.0
Drawbar pull, with/without load	N	600
Maximum drawbar pull, with/ without load	N	1320
Maximum gradeability, with/ without load	%	10/15
Acceleration time, with / without load (0-10m)	s	5.7/4.7
Battery voltage/nominal capacity	V/Ah	24/105
Battery weight	kg	75

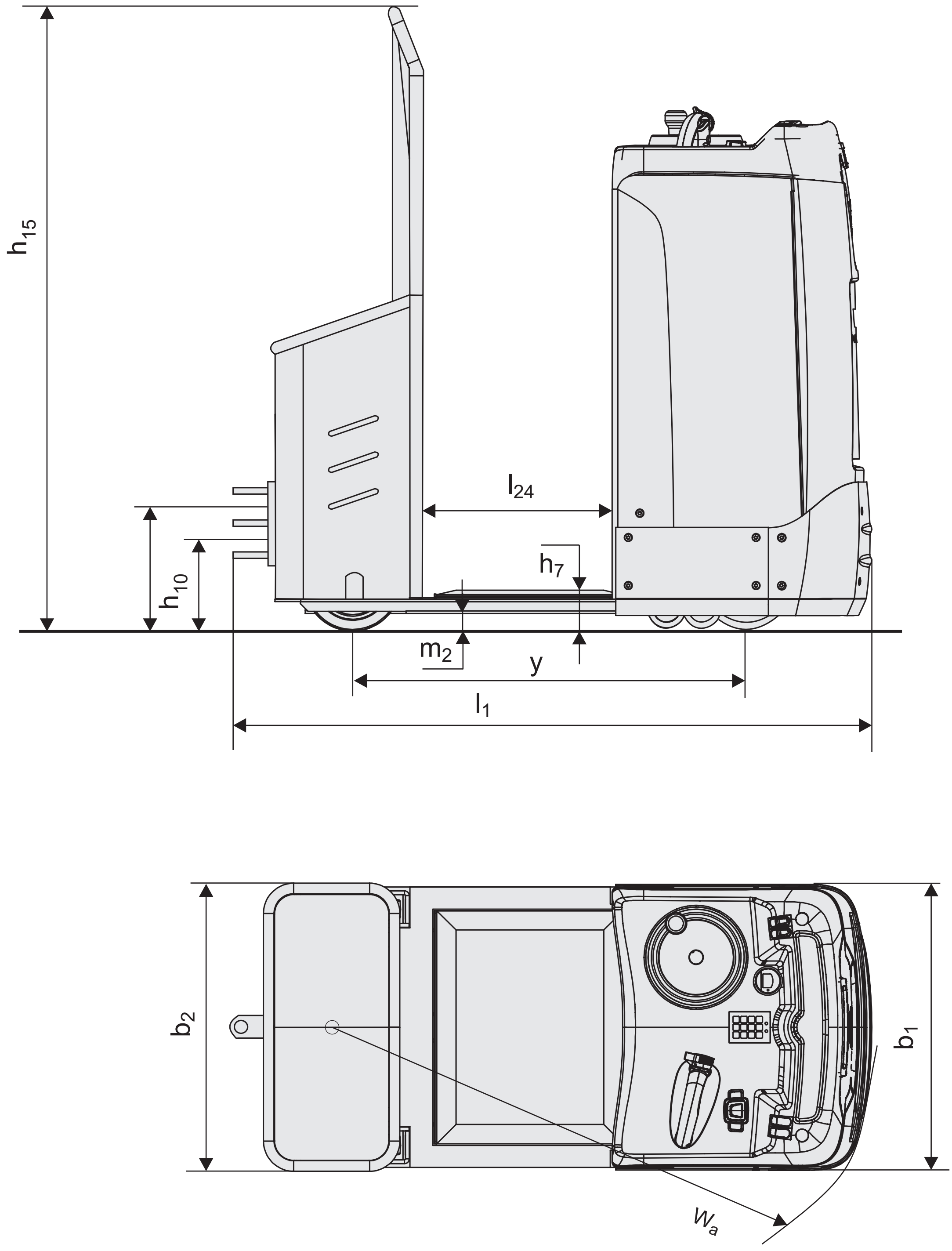


Figure A.1: Technical drawing of Toyota's towing truck model TSE150-708 [51]

A.2 Toyota's hand pallet truck LHM230

Table A.2: Toyota's hand pallet truck LHM230's technical specification [51]

Parameter	Unit of measurement	Value
Manufacturer	-	BT
Model	-	LHM230
Operator type	-	Hand
Drive	-	Electric
Load capacity (Q)	kg	$2,300$
Load centre distance (c)	mm	600
Load distance, centre of drive axle to fork (x)	mm	945
Wheelbase (y)	mm	1170
Service weight	kg	63
Wheel size, front	mm	175 x 60
Wheel size, rear	mm	85 x 100
Track width, front (b_{10})	mm	132
Track width, rear (b_{11})	mm	364
Lift (h_3)	mm	115
Lift height (h_{23})	mm	200
Height of tiller in drive position, min./max. (h_{14})	mm	1220
Height, lowered (h_{13})	mm	85
Overall length (l_1)	mm	1500
Length to face of forks (l_2)	mm	365
Overall width (b_1/b_2)	mm	520/685
Fork dimensions ($s/e/l$)	mm	45/156/1150
Width over forks (b_5)	mm	520
Ground clearance, centre of wheelbase (m_2)	mm	40
Aisle width for pallets 1000 x 1200 crossways (A_{st})	mm	1525
Aisle width for pallets 800 x 1200 lengthways (A_{st})	mm	1725
Turning radius (w_a)	mm	1370

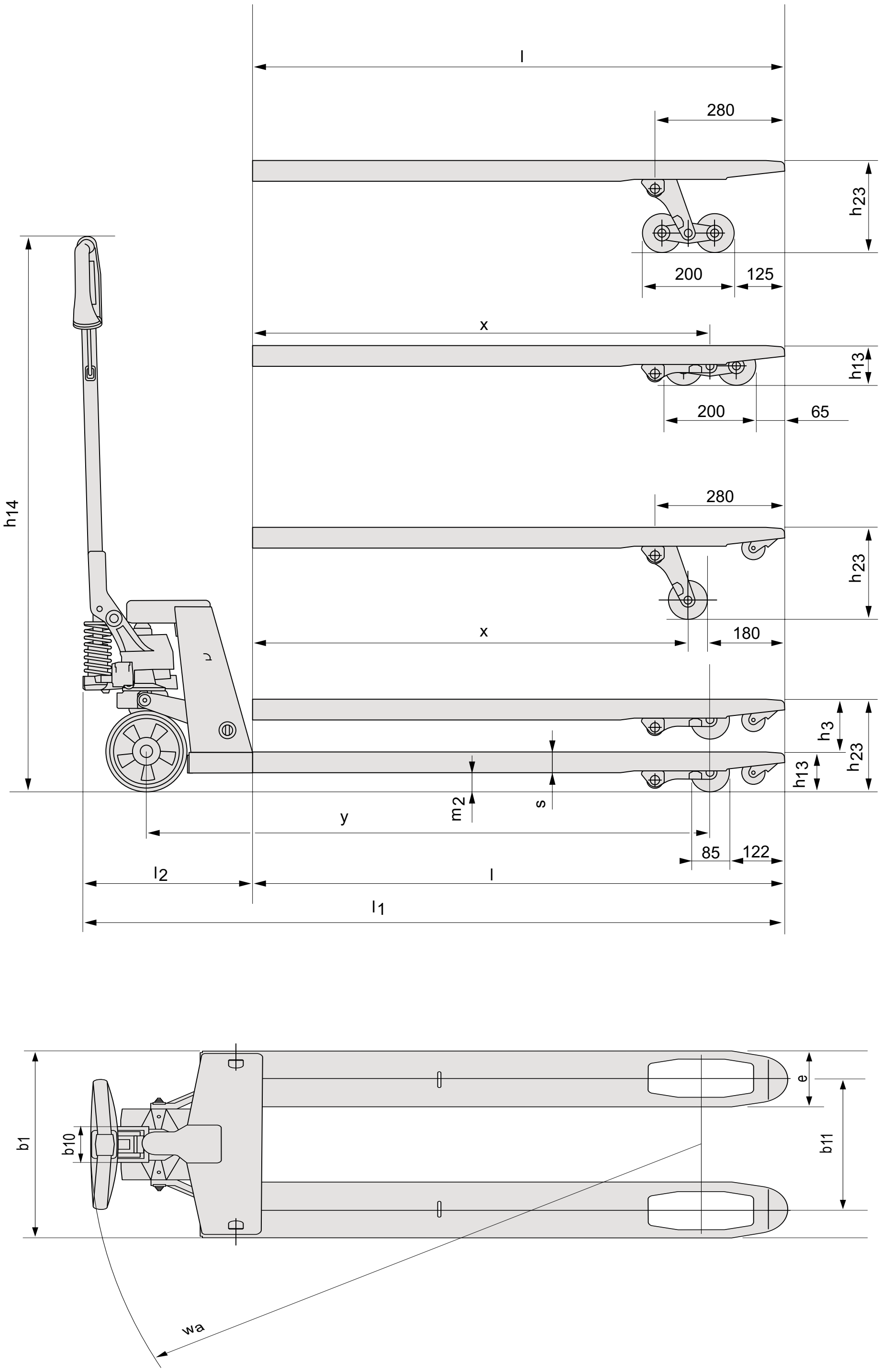


Figure A.2: Technical drawing of Toyota's hand pallet truck model LHM230 [52]

A.3 Indeva AGVs technical specifications

Table A.3: Indeva's AGV models technical specification [53]

Parameter	**Tugger/Tunnel 750 kg**	**Tugger 1,500 kg**
Power supply	24 V, DC	48 V, DC
Drive unit type	DC motor brushless	DC motor brushless
Drive unit power	100W x 2	400W x 2
Max. towing capacity	750 kg	1,500 kg
Towing force	350 N	700 N
Maximum speed	50 m/min	50 m/min
Guidance system	Magnetic	Magnetic
Direction	Forward	Forward
Steering system	Differential speed	Differential speed
Min. turning radius	600 mm	1000 mm
Stop precision	±30 mm	±30 mm
Battery voltage	Set of 24V (2x12V)	Set of 48V (4x12V)
Battery capacity	40Ah or 70Ah	135Ah
Battery run time	6h (40Ah), 10h (70Ah)	16h
Programs	56 programs	56 programs
Dimensions Tugger	965 x 544 x 1,500 mm	1,400 x 920 x 1,150 mm
Dimensions Tunnel	1,350 x 570 x 450 mm	-
Obstacle sensor	SICK Laser Scanner 8z	SICK Laser Scanner 8z

Safety: in accordance with all relevant standards (EN1525, EN13839): obstacle sensor, flashing lamp, melody unit, emergency stop button, turn indicators (optional).

Appendix B

Matlab® codes

B.1 Code for alternatives 1 and 2 simulation

The Matlab ® code used to simulate the performance of alternatives 1 and 2 is reported in Appendix B.1.1. The code uses a set of auxiliary functions, whose codes are reported in Appendix B.1.2.

The main code reads an external *txt* file in which the production volumes are described. The file reports all FGs produced in one day, the type of packaging material used by each one, the quantity produced, and the time each box is released from cells.

The parameters of the simulation are set at the beginning of the code - the number of routes performed per day, the estimated duration of each route, and the towing truck's transporting capacity. The initial values of variables are also set.

The main routine consists of a loop in time. The time interval between two loops is not fixed; a new loop is initiated every time a new box is produced. Between two consecutive routes, the queued volumes in each cell are updated when a new box is produced. When a route is scheduled to be performed, it is supposed that the towing truck picks up all the boxes that fit its wagons, and the queued volumes decrease uniformly along the route's duration. At the end of the route, the queued volumes are updated with the boxes produced while the truck was performing the activity. The simulation runs until the time instant T_sim is reached (correspondent to the end of the working hours in the plant).

At the end of the simulation, the system performance indicators (average total queued volume and transporting capacity utilization) are calculated. The matrix containing the values of total queued volume at each time instant is stored in a *txt* file. Finally, the total queued volume versus time curve is plotted.

If the simulation is held for alternative 2, the code should be run individually for each of the routes. The production file should consider only the boxes produced by cells that belong to the studied route, and the route's estimated duration should correspond to the same route.

The detailed explanation about the code of each function is provided as comments in the code.

B.1.1 Main code

```
clear all
n_nodes=45;

% Box production file:
% | Node | t | FG.A | FG.B | FG.C | FG.D | FG.E |
% | COMP.A | COMP.B | COMP.C | COMP.D | COMP.E | Add. |
% read file with box production
fileID_box=fopen('current_input.txt','r');
formatSpec='%f';
BoxProd_aux=fscanf(fileID_box,formatSpec);
% organize node position matrix
ncol=7;
nlinaux=size(BoxProd_aux);
nlin=nlinaux(1,1);
BoxProd=zeros(nlin/ncol,ncol);
for i=1:ncol:nlin
    a=(i-1)/ncol+1;
    for j=1:1:ncol
        BoxProd(a,j)=BoxProd_aux(i+j-1,1);
    end
end

% Parameters of the simulation:
% number of routes
n_routes=34;
% duration of route (s)
d_route=15.75*60;
% simulation duration
T_sim=16*3600;
capacity=3*0.9;
capacity_util=3;

% Cum_qty reports the accumulated number of
% boxes in cells for each packaging category:
% | CAT.A | CAT.B | CAT.C | CAT.D | CAT.E |
Cum_qty=zeros(1,5);
for i=1:1:5
   Cum_qty(1,i)=BoxProd(1,i+2);
end

% Initial value for the variables:
t=BoxProd(1,2);
q_tot=zeros(500,2);
```

```
q_tot(1,1)=0;
q_tot(1,2)=6/24+2/6;
q_tot(2,1)=t-0.01;
q_tot(2,2)=6/24+2/6;
q_tot(3,1)=t;
q_tot(3,2)=q_tot(2,2)+BoxProd(1,3)/24+BoxProd(1,4)/6
      +BoxProd(1,5)/3+BoxProd(1,6)/1+BoxProd(1,7)/12;
n_routes_done=0;
n=0;

% MAIN ROUTINE:
while t<T_sim % run until simulation duration is reached
    n=n+1;
    % Calculates the instant at which the next route
    % should be performed:
    t_next_pick=(n_routes_done+1)*(T_sim-d_route-50)/
                n_routes;
    % Verifies the instant at which the next box is
    % produced:
    t_next_prod=calc_next(t,BoxProd);
    % If the next box is produced before the next route:
    if t_next_prod<t_next_pick
        if t_next_prod>t
            t=t_next_prod;
        else
            t=t+0.01;
        end
        q_tot(2*n+2,1)=t-0.01;
        q_tot(2*n+2,2)=q_tot(2*n+1,2);
        % Updates the total accumulated volume in cells:
        Cum_qty=update_acum(Cum_qty,t_next_prod,BoxProd);
        q_tot(2*n+3,1)=t;
        q_tot(2*n+3,2)=Cum_qty(1,1)/24+Cum_qty(1,2)/6+
          Cum_qty(1,3)/3+Cum_qty(1,4)/1+Cum_qty(1,5)/12;
    % If the next route is to be performed before the next
    % box is produced:
    else
        t=t_next_pick;
        % Update the number of routes already performed:
        n_routes_done=n_routes_done+1;
        q_tot(2*n+2,1)=t;
        q_tot(2*n+2,2)=q_tot(2*n+1,2);
        % Towing truck picks up all the boxes within the
        % routes duration (up to its transporting capacity):
        [q_picked,Cum_qty]=pickup(Cum_qty,capacity);
        q_tot(2*n+3,1)=t+d_route;
```

```
        q_tot(2*n+3,2)=q_tot(2*n+1,2)-q_picked;
        % Updates the queued volumes in cells with the boxes
        % that were produced during the route of the towing
        % truck.
        Cum_qty=between(t,t+d_route,BoxProd,Cum_qty);
        n=n+1;
        t=t+d_route;
        q_tot(2*n+2,1)=t+0.01;
        q_tot(2*n+2,2)=q_tot(2*n+1,2);
        q_tot(2*n+3,1)=t+0.02;
        q_tot(2*n+3,2)=Cum_qty(1,1)/24+Cum_qty(1,2)/6+
          Cum_qty(1,3)/3+Cum_qty(1,4)/1+Cum_qty(1,5)/12;
    end

end

% Calculate the average total queued volume:
dt=0.03;
int=0;
n_others=0;
rec=zeros(n,1);
int_rec(1,2)=0;
util=zeros(n_routes,1);
for i=1:1:n
    if (q_tot(2*i+1,1)-q_tot(2*i,1))<dt
        int=int+(q_tot(2*i,1)-q_tot(2*i-1,1))*q_tot(2*i,2);
    else
        int=int+(q_tot(2*i,1)-q_tot(2*i-1,1))*q_tot(2*i,2)+
            (q_tot(2*i+1,1)-q_tot(2*i,1))*(q_tot(2*i,2)+
            q_tot(2*i+1,2))/2;
        n_others=n_others+1;
        util(n_others,1)=(q_tot(2*i,2)-q_tot(2*i+1,2))/
            capacity_util;
    end
    int_rec(i+1,1)=q_tot(2*i,1);
    int_rec(i+1,2)=int;
end
% Average utilization of the towing truck's transporting
% capacity:
avg_utilization=mean(util(:,1));
% Average total queued volume:
avg_qtot=int/T_sim;

% Save total queue vs time in txt file:
link=strcat('tot_queue_CURRENT_today.txt');
fileID = fopen(link,'w');
```

```
fprintf(fileID,'%1f %3f\n',q_tot(1:2*n+2,1),
                    q_tot(1:2*n+2,2));
fclose(fileID);

% Plot total accumulated volume versus time:
figure
plot(q_tot(1:2*n+2,1)/3600,q_tot(1:2*n+2,2),'Color',
                                      [0.069,0.334,0.597])
xlim([0 16])
ylim([0 6])
title('Total queue (quantity to be transported)
 versus time')
xlabel('Time [h]')
ylabel('Queued quantity [wagons]')
```

B.1.2 Auxiliary functions

```
function [ t_next ] = calc_next( t,BoxProd )
%   Calculates the instant at which the next box is
%   produced starting from instant t.
  aux=size(BoxProd);
  a=aux(1,1);

  t_at=0;
  n=0;
  while t_at<=t
      n=n+1;
      t_at=BoxProd(n,2);
      t_next=t_at;
      if n==a
         t_at=16*3600;
         t_next=t_at;
      end
  end
end


function [ Cum_qty_new ] = update_acum( Cum_qty,t,BoxProd )
%   Returns the updated total queued volume in cells
%   considering the produced boxes in instant t.
  Cum_qty_new=Cum_qty;
  aux=size(BoxProd);
  a=aux(1,1);
```

```
  for i=1:1:a
      if BoxProd(i,2)==t
          for j=1:1:5
            Cum_qty_new(1,j)=Cum_qty_new(1,j)+
              BoxProd(i,j+2);
          end
      end
  end
end


function [ q_picked,Cum_qty_new ] = pickup ( Cum_qty_old,
                                              capacity )
%   Returns the total quantity that can be picked up
%   (taking into account the truck's transporting capa-
%   city) and the new accumulated volume.

  Cum_qty_new=Cum_qty_old;
  space=capacity;
  q_picked=0;
  % correspondence matrix:
  %    Cat.A -> n_cat=1, 24 per wagon
  %    Cat.B -> n_cat=2, 06 per wagon
  %    Cat.C -> n_cat=3, 03 per wagon
  %    Cat.D -> n_cat=4, 01 per wagon
  %    Cat.E -> n_cat=5, 12 per wagon
  % Priority level: Cat.D>Cat.C>Cat.B>Cat.E>Cat.A
  cats=[4,1;3,3;2,6;5,12;1,24];

  % Evaluate the maximum volume that can be picked
  % up from the transporting capacity viewpoint.
  for i=1:1:5
     cat_number=cats(i,1);
     boxperwagon=cats(i,2);
     [ n_box ] = maxpickup ( space,boxperwagon,
                          Cum_qty_new(1,cat_number) );
     space=space-n_box/boxperwagon;
     Cum_qty_new(1,cat_number)=Cum_qty_new(1,cat_number)
                                                 -n_box;
     q_picked=q_picked+(Cum_qty_old(1,cat_number)-
       Cum_qty_new(1,cat_number))/boxperwagon;
  end
end
```

```
function [ n_box_canpick ] = maxpickup( space,
                               boxperwagon, n_box_tot )
%   Returns the maximum number of boxes of a specific
%   pack. category that can be picked up by the truck,
%   considering the available space in the truck's wagons.
  n_box_canpick=0;
  stop=0;
  % if all boxes fit on available space:
  if space>=n_box_tot/boxperwagon
     n_box_canpick=n_box_tot;
  % if not all the boxes fit on available space:
  else
      % fills until there is no available space:
      while stop==0
          if  space<1/boxperwagon
             stop=1;
          else
             n_box_canpick=n_box_canpick+1;
             space=space-1/boxperwagon;
          end
      end
  end
end


function [ Q_cum ] = between ( t_i, t_f, BoxProd, Cum_qty )
%   Updates the queued volumes in cells with the boxes
%   produced between instants t_i and t_f.
  aux=size(BoxProd);
  a=aux(1,1);
  % Initially both are identical:
  Q_cum=Cum_qty;

  % Checks if boxes were produced between t_i and
  % t_f for each packaging category
  for i=1:1:a
     if BoxProd(i,2)>=t_i && BoxProd(i,2)<=t_f
        Q_cum(1,1)=Q_cum(1,1)+BoxProd(i,3);
        Q_cum(1,2)=Q_cum(1,2)+BoxProd(i,4);
        Q_cum(1,3)=Q_cum(1,3)+BoxProd(i,5);
        Q_cum(1,4)=Q_cum(1,4)+BoxProd(i,6);
        Q_cum(1,5)=Q_cum(1,5)+BoxProd(i,7);
     end
  end
end
```

B.2 Code for alternative 3 simulation

The Matlab ® code used to simulate the performance of the alternative 3 is reported in Appendix B.2.1. The code uses a set of auxiliary functions, whose codes are reported in Appendix B.2.2.

The main code reads two external *txt* files. The first one reports all FGs produced in one day, the type of packaging material used by each one, the quantity produced, and the time each box is released from cells. The second one reports the *x,y* coordinates of each node and the distance to the adjacent nodes.

The parameters of the simulation are set at the beginning of the code - the AGV's transporting capacity, its average speed, the tuning parameters, the average waiting time, and the loading and unloading times. The initial values of variables are also set.

The code uses two auxiliary matrices: the accumulated quantity-time matrix (which reports the accumulated volumes in each cell and their correspondent waiting time) and the ranking matrix (which reports the ranking parameter for each cell, as described in Section 6.3).

The main routine consists of a loop in time. The time interval between two loops is not fixed; a new loop is initiated every time the AGV passes through a node. The queued volumes in each cell are updated when a new box is produced. At each loop, it is verified whether the AGV has an objective (a node it should go to). If the objective is identified, the adjacent node towards which the AGV should go is chosen by following the methodology reported in Section 6.3. If a workcell is reached, the boxes already produced by the cell are loaded up to the AGV's transporting capacity. If fully loaded, it sets the FGQC station as objective. When arriving at the FGQC cell, the drop-off point is chosen as the next objective.

On the other hand, if the AGV does not have any objective, it is verified whether there are any boxes waiting to be picked up. If positive, the ranking matrix is updated and the next objective is set. If negative, the AGV waits for the next box to be produced. The simulation runs until the time instant T_sim is reached (correspondent to the end of the working hours in the plant).

At the end of the simulation, parameters and system performance indicators (average total queued volume, transporting capacity utilization, total distance traveled, average waiting time, and the number of routes performed) are calculated and stored into a *txt* file. The matrix containing the values of total queued volume at each time instant is also stored in a *txt* file. Finally, the total queued volume versus time curve is plotted.

The detailed explanation about the code of each function is provided as comments in the code.

B.2.1 Main code

```
clear all
n_nodes=45;

% Node position file:
% File that reports, for each node, the adjacent nodes
% to it and the distance to each of them.
% The file has the following format:
% | Node | x | y | dir.1 | dir.2 | dir.3 | dir.4 |
%        | d1 | d2 | d3 | d4 |
% read file with node positions
fileID_nodes=fopen('node_matrix.txt','r');
formatSpec='%f';
Nodes_aux=fscanf(fileID_nodes,formatSpec);
% organize node position matrix
ncol=11;
nlinaux=size(Nodes_aux);
nlin=nlinaux(1,1);
Nodes=zeros(nlin/ncol,ncol);
for i=1:ncol:nlin
    a=(i-1)/ncol+1;
    for j=1:1:ncol
        Nodes(a,j)=Nodes_aux(i+j-1,1);
    end
end

% Box production file:
% | Node | t | FG.A | FG.B | FG.C | FG.D | FG.E |
% | COMP.A | COMP.B | COMP.C | COMP.D | COMP.E | Add. |
% read file with box production
fileID_box=fopen('box_production_cat.txt','r');
formatSpec='%f';
BoxProd_aux=fscanf(fileID_box,formatSpec);
% organize node position matrix
ncol=13;
nlinaux=size(BoxProd_aux);
nlin=nlinaux(1,1);
BoxProd=zeros(nlin/ncol,ncol);
for i=1:ncol:nlin
    a=(i-1)/ncol+1;
    for j=1:1:ncol
        BoxProd(a,j)=BoxProd_aux(i+j-1,1);
    end
end
```

```
% SIMULATION:
n_sim='01'; % identifying number of the simulation
% Parameters of the simulation:
capacity=3; % AGV's transporting capacity (# wagons)
v_kmh=2.25; % AGV's average speed (km/h)
alpha=0.5; % distance-related tuning parameter
beta=0.5; % time-related tuning parameter
shift_h=16; % working time in hours
t_perbox=10; % time required to load per box
t_wait=100; % waiting time (at each cell)
t_unload=45; % time dedicated to unload AGV (s)
T_sim_h=16; % simulation period (h)


% Ranking matrix:
% Matrix that reports the ranking index for each node.
% The matrix has the following format:
% | Node | distance | queue time | psi |
Rank=zeros(n_nodes,4);

% Accumulated quantity-time matrix:
% Matrix that report the accumulated boxes in the different
% nodes and the waiting time.
% The matrix has the following format:
% | Node | FG.A | FG.B | FG.C | FG.D | FG.E |
% | COMP.A | COMP.B | COMP.C | COMP.D | COMP.E | Add. |
% | t_initial | t_cum |
Cum_matrix=zeros(n_nodes,14);
Cum_matrix(:,1)=Nodes(:,1);

% Conversions:
v=v_kmh/3.6; % v: speed in m/s
shift=shift_h*3600; % shift duration in s
T_sim=T_sim_h*3600; % simulation duration in s

% Initial values for the variables:
node_agv=1;
node_obj=0;
node_prv=101;
t_old=0;
t=0;
D_tot=0;
q_transp=0;
n_routes=0;
q_cum_tot=0;
```

```
record_cum=zeros(10000,2);
n_cum=0;
record_dep=zeros(1000,2);
n_picks=0;
t_parado=0;
buffer=zeros(n_nodes,2);
n_buf=0;
maxbuff=zeros(2000,3);
buffer(:,1)=Cum_matrix(:,1);
twaittot=zeros(2000,1);
n_wait=0;
n_int=0;


% MAIN ROUTINE:
while t<=T_sim

    % If there is an objective:
    if node_obj~=0
        if node_agv==node_obj
         % if AGV is in drop-off point, it unloads:
         if node_agv==1
             n_routes=n_routes+1;
             % time in which it unloads:
             record_dep(n_routes,1)=t;
             if n_routes==1
                  % quantity unloaded:
                  record_dep(n_routes,2)=q_transp;
             else
                  % quantity unloaded
                  record_dep(n_routes,2)=record_dep(n_routes-1,2)
                  +q_transp;
             end
             q_transp=0;
             t=t+t_wait+t_unload;
             node_obj=0;
         % if AGV is in FGQC, send to drop-off point:
         elseif node_agv==10
             t=t+t_wait+t_perbox*4;
             node_obj=1;
             n_picks=n_picks+1;


         else % if AGV is in a cell, loads AGV
             n_wait=n_wait+1;
             for k=1:1:n_nodes
```

```
            if Cum_matrix(k,1)==node_agv
                twaittot(n_wait,1)=Cum_matrix(k,14);
            end
        end
        % update q_transp and Cum_matrix:
        [Cum_matrix,q_transp,nbox,node_obj]=
        load_cat_op1(node_agv,Cum_matrix,capacity,
          q_transp);
        t=t+t_wait+nbox*t_perbox;
        n_picks=n_picks+1;
        for k=1:1:n_nodes
            buffer(k,2)=(Cum_matrix(k,2)+
            Cum_matrix(k,7))/24+(Cum_matrix(k,3)+
            Cum_matrix(k,8))/6+(Cum_matrix(k,4)+
            Cum_matrix(k,9))/3+(Cum_matrix(k,5)+
            Cum_matrix(k,10))/1+(Cum_matrix(k,6)+
            Cum_matrix(k,11))/12;
        end
        n_buf=n_buf+1;
        maxbuff(n_buf,1)=t;
        maxbuff(n_buf,2)=max(buffer(:,2));
        for k=1:1:n_nodes
            if buffer(k,2)==maxbuff(n_buf,2)
                maxbuff(n_buf,3)=buffer(k,1);
            end
        end
    end

    % if node_agv is different from node_obj,
    % go towards the objective:
    else
         node_nxt=next_node(node_agv,node_prv,
          node_obj,Nodes);
         node_prv=node_agv;
         node_agv=node_nxt;
         dist=dist_nodes(node_agv,node_prv,Nodes);
         D_tot=D_tot+dist;
         t=t+dist/v;
    end


else % if there is no objective set:
    % update production:
    Cum_matrix=update_cum_op1(Cum_matrix,BoxProd,t_old,t);
    t_old=t;
    q_cum_tot=(sum(Cum_matrix(:,2))+
```

```
sum(Cum_matrix(:,7)))/24+(sum(Cum_matrix(:,3))+
sum(Cum_matrix(:,8)))/6+(sum(Cum_matrix(:,4))+
sum(Cum_matrix(:,9)))/3+(sum(Cum_matrix(:,5))+
sum(Cum_matrix(:,10)))/1+(sum(Cum_matrix(:,6))+
sum(Cum_matrix(:,11)))/12;
n_cum=n_cum+1;
% save the updated total accumulated quantity:
record_cum(n_cum,1)=t;
record_cum(n_cum,2)=q_cum_tot;
for k=1:1:n_nodes
    buffer(k,2)=(Cum_matrix(k,2)+
    Cum_matrix(k,7))/24+(Cum_matrix(k,3)+
    Cum_matrix(k,8))/6+(Cum_matrix(k,4)+
    Cum_matrix(k,9))/3+(Cum_matrix(k,5)+
    Cum_matrix(k,10))/1+(Cum_matrix(k,6)+
    Cum_matrix(k,11))/12;
end
n_buf=n_buf+1;
maxbuff(n_buf,1)=t;
maxbuff(n_buf,2)=max(buffer(:,2));
for k=1:1:n_nodes
   if buffer(k,2)==maxbuff(n_buf,2)
        maxbuff(n_buf,3)=buffer(k,1);
   end
end
% if there are no boxes to be transported
% and no boxes on the AGV, wait until next box:
if and(q_cum_tot==0,q_transp==0)
     if t>shift
         T_final=t;
         t=T_sim+0.1;
     else
          t=t_next_box(t,BoxProd);
     end
% if the AGV is loaded and there is no box to
% be picked up, set FGQC as objective:
elseif q_cum_tot==0
     node_obj=10;

% if there are boxes to be picked up and the
% AGV is unloaded/not fully loaded, go get boxes:
else
     Rank=calc_rank_op1(Cum_matrix,Nodes,node_agv,
            alpha,beta);
     node_obj=highest_psi(Rank);
end
```

```
    end
    n_int=n_int+1;
end

% Make plot flat between 2 points (accumulated qty)
rec_cumfin=zeros(2*n_cum,2);
integral=zeros(n_cum,1);
for i=1:1:n_cum
    rec_cumfin(2*i-1,1)=record_cum(i,1);
    rec_cumfin(2*i-1,2)=record_cum(i,2);
    rec_cumfin(2*i,1)=record_cum(i+1,1)-0.0001;
    rec_cumfin(2*i,2)=record_cum(i,2);
    integral(i,1)=record_cum(i,2)*(rec_cumfin(2*i,1)
     -rec_cumfin(2*i-1,1));
end

utilization=record_dep(n_routes,2)/n_routes/capacity;
n_waittot=0;
for k=1:1:2000
    if twaittot(k,1)~=0
       n_waittot=n_waittot+1;
    end
end


% Save parameters and results in txt file:
link=strcat('par_res_sim',n_sim,'.txt');
Results=zeros(15,1);
% PARAMETERS
Results(1,1)=capacity;
Results(2,1)=alpha;
Results(3,1)=beta;
Results(4,1)=v_kmh;
Results(5,1)=t_perbox;
Results(6,1)=t_unload;
Results(7,1)=t_wait;
% RESULTS
Results(8,1)=utilization;
Results(9,1)=n_routes;
Results(10,1)=D_tot;
Results(11,1)=sum(integral(:,1))/T_final;
Results(12,1)=max(maxbuff(:,2));
Results(13,1)=(T_final-16*3600)/3600;
Results(14,1)=n_picks;
Results(15,1)=sum(twaittot(:,1))/n_waittot;
```

```
fileID = fopen(link, 'w');
fprintf(fileID, '%6.4f \n', Results);
fclose(fileID);

% Save data in txt file
link=strcat('tot_queue_sim', n_sim, '.txt');
fileID = fopen(link, 'w');
fprintf(fileID, '%1f %3f\n', rec_cumfin(:,1),
 rec_cumfin(:,2));
fclose(fileID);

% Plot of total accumulated quantity versus time
figure
plot(rec_cumfin(:,1)/3600, rec_cumfin(:,2))
xlim([0 17])
ylim([0 4])
title('Total queue (quantity to be transported)
      versus time')
xlabel('Time [h]')
ylabel('Queued quantity [wagons]')
```

B.2.2 Auxiliary functions

```
function [ Cum_matrix_new, q_transp_new, n_boxes, node_obj ]
          = load_cat_op1( node, Cum_matrix_old, capacity,
                          q_transp_old )
%   When AGV stops at a node to load the boxes, the
%   function returns the new transported quantity,
%   the updated accumulated matrix and the number of
%   boxes loaded.

  Cum_matrix_new=Cum_matrix_old; % initially
  q_transp_new=q_transp_old; % initially
  aux=size(Cum_matrix_old);
  a=aux(1,1);

  % find line correspondant to node and copy data:
  for i=1:1:a
      if Cum_matrix_old(i,1)==node
          cum_node=Cum_matrix_old(i,:);
```

```
        n_line=i;
    end
end

% evaluate how many boxes fit on the wagons
available_space=capacity-q_transp_new;

% sum FG+components for each box category
cat_cum(1,1)=cum_node(1,2)+cum_node(1,7); % Cat.A
cat_cum(1,2)=cum_node(1,3)+cum_node(1,8); % Cat.B
cat_cum(1,3)=cum_node(1,4)+cum_node(1,9); % Cat.C
cat_cum(1,4)=cum_node(1,5)+cum_node(1,10); % Cat.D
cat_cum(1,5)=cum_node(1,6)+cum_node(1,11); % Cat.E

% correspondence matrix:
%    Cat.A -> n_cat=1, 24 per wagon
%    Cat.B -> n_cat=2, 06 per wagon
%    Cat.C -> n_cat=3, 03 per wagon
%    Cat.D -> n_cat=4, 01 per wagon
%    Cat.E -> n_cat=5, 12 per wagon
% Priority level: Cat.D>Cat.C>Cat.B>Cat.E>Cat.A
cats=[4,1;3,3;2,6;5,12;1,24];
n_boxes=0; % initial value

for i=1:1:5
    cat_number=cats(i,1);
    boxperwagon=cats(i,2);
  % if there are boxes of this category to be transported:
  if cat_cum(1,cat_number)~=0
      [Cum_matrix_new, q_transp_extra, nbx]=
       update_load(Cum_matrix_new, n_line,
       cat_cum(1,cat_number), available_space,
       boxperwagon, cat_number);
      q_transp_new=q_transp_new+q_transp_extra;
      n_boxes=n_boxes+nbx;
      available_space=capacity-q_transp_new;
  end
end

tot_boxes=sum(Cum_matrix_new(n_line,2:11));

if tot_boxes==0 % finished all boxes
   node_obj=0; % decide next cell to go
else
   node_obj=10; % go to FGQC and then deposit
end
```

```
end


function [ node_next ] = next_node ( node_agv ,node_prv ,
                              node_obj ,Nodes_matrix )
%   Determines the next node the AGV should go in order
%   to reach the objective node, considering the current
%   node and the previous node.

  % calculate distance for each node
  d=zeros(1,4);
  line=line_node(node_agv,Nodes_matrix);
  for i=1:1:4
      if or(Nodes_matrix(line,3+i)==node_prv,
                    Nodes_matrix(line,3+i)==0)
          d(1,i)=10000;
      else
           d(1,i)=dist_nodes(node_obj,
                    Nodes_matrix(line,3+i),Nodes_matrix);
      end
  end

  % find smallest distance
  d_min=min(d);
  for i=1:1:4
      if d(1,i)==d_min
          n_node=i;
      end
  end

  node_next=Nodes_matrix(line,3+n_node);
end


function [d] = dist_nodes(origin_node,dest_node,matrix)
%   Determines distance between origin node and
%   destination node.

  aux=size(matrix);
  a=aux(1,1);
  % find x,y position of origin and destination nodes:
  for i=1:1:a
      if matrix(i,1)==origin_node
          x_o=matrix(i,2);
          y_o=matrix(i,3);
```

```
        end
        if matrix(i,1)==dest_node
            x_d=matrix(i,2);
            y_d=matrix(i,3);
        end
    end
    % Calculate distance
     d=sqrt((x_o-x_d)^2+(y_o-y_d)^2);
end


function [Cum_matrix_new] = update_cum_op1(Cum_matrix_old,
                                  prod_matrix,t_old,t_new)
%   Updates the accumulated matrix with the production in
%   the period between t_old and t_new (considering boxes
%   categories and components).

     aux=size(Cum_matrix_old);
     a=aux(1,1);
     Cum_matrix_new=Cum_matrix_old;
     aux2=size(prod_matrix);
     b=aux2(1,1);

     % update queue time (for all nodes already waiting):
     for j=1:1:a
          if sum(Cum_matrix_new(j,2:11))~=0
               Cum_matrix_new(j,14)=t_new-Cum_matrix_new(j,13);
          end
     end

     % update quantity (only if there are new boxes produced):
     for i=1:1:b
         if and(prod_matrix(i,2)<=t_new,prod_matrix(i,2)>t_old)
              node=prod_matrix(i,1);
              %j=line_node(node,Cum_matrix_new);
              for k=1:1:a
                   if Cum_matrix_new(k,1)==node
                       j=k;
                   end
              end

              % it is a new box, so record initial time
              if sum(Cum_matrix_new(j,2:11))==0
                   Cum_matrix_new(j,13)=prod_matrix(i,2);
              end
              % update quantities
```

```
                Cum_matrix_new(j,2)=Cum_matrix_new(j,2)+
                                     prod_matrix(i,3);
                Cum_matrix_new(j,3)=Cum_matrix_new(j,3)+
                                     prod_matrix(i,4);
                Cum_matrix_new(j,4)=Cum_matrix_new(j,4)+
                                     prod_matrix(i,5);
                Cum_matrix_new(j,5)=Cum_matrix_new(j,5)+
                                     prod_matrix(i,6);
                Cum_matrix_new(j,6)=Cum_matrix_new(j,6)+
                                     prod_matrix(i,7);
                Cum_matrix_new(j,7)=Cum_matrix_new(j,7)+
                                     prod_matrix(i,8);
                Cum_matrix_new(j,8)=Cum_matrix_new(j,8)+
                                     prod_matrix(i,9);
                Cum_matrix_new(j,9)=Cum_matrix_new(j,9)+
                                     prod_matrix(i,10);
                Cum_matrix_new(j,10)=Cum_matrix_new(j,10)+
                                     prod_matrix(i,11);
                Cum_matrix_new(j,11)=Cum_matrix_new(j,11)+
                                     prod_matrix(i,12);
                Cum_matrix_new(j,12)=Cum_matrix_new(j,12)+
                                     prod_matrix(i,13);

                % check if Cat.A fractions are completed
                if Cum_matrix_new(j,12)>=1
                    Cum_matrix_new(j,7)=Cum_matrix_new(j,7)+
                    floor(Cum_matrix_new(j,12));
                    Cum_matrix_new(j,12)=Cum_matrix_new(j,12)-
                    floor(Cum_matrix_new(j,12));
                end

            end
        end

end


function [ Rank_matrix ] = calc_rank_op1( Cum_matrix,
                    Node_matrix, node_agv, alpha, beta )
%   Calculates the ranking matrix given the accumulated
%   quantities/queue time and the AGV's position.

    aux=size(Node_matrix);
    a=aux(1,1);
    Rank_matrix=zeros(a,5);
    Rank_matrix(:,1)=Node_matrix(:,1);
```

```
% Calculate distance and t_cum
for i=1:1:a
   % if there are boxes to be moved:
   if sum(Cum_matrix(i,2:11))~=0
       % Distance:
       Rank_matrix(i,3)=dist_nodes(node_agv,
         Rank_matrix(i,1),Node_matrix);
       % Accumulated time:
       Rank_matrix(i,4)=Cum_matrix(i,14);
   end

end

% Calculate ranking parameter psi
d_tot=sum(Rank_matrix(:,3));
t_cum_tot=sum(Rank_matrix(:,4));
d_rank=zeros(a,1);
t_rank=zeros(a,1);
% calculate t_rank
if d_tot==0
   d_rank=zeros(a,1);
else
    for i=1:1:a
        if Rank_matrix(i,3)==0
            d_rank(i,1)=0;
        else
            d_rank(i,1)=alpha*d_tot/Rank_matrix(i,3);
        end
    end

end

% calculate t_rank
if t_cum_tot==0
   t_rank=zeros(a,1);
else
    for i=1:1:a
        if Rank_matrix(i,4)==0
            t_rank(i,1)=0;
        else
            t_rank(i,1)=beta*Rank_matrix(i,4)/t_cum_tot;
        end
    end

end
```

```
    % finally calculate last column of Ranking matrix
    for i=1:1:a
        Rank_matrix(i,5)=d_rank(i,1)+t_rank(i,1);
    end

end


function [ node ] = highest_psi( Rank_matrix )
%   Returns the node with the highest psi value (node
%   towards which the AGV should go)

  aux=size(Rank_matrix);
  a=aux(1,1);
  % highest psi value
  psi_max=max(Rank_matrix(:,5));
  % find node correspondant to this psi_max
  if psi_max==0
      node=0;
  else
      for i=1:1:a
          if Rank_matrix(i,5)==psi_max
              node=Rank_matrix(i,1);
          end
      end
  end
end


function [t_next] = t_next_box(t,prod_matrix)
%   Returns the time in which the next box is produced
%   (starting from instant t).

  aux=size(prod_matrix);
  a=aux(1,1);
  i=1;
  resp=0;
  while resp==0
      if prod_matrix(i,2)>t
          t_next=prod_matrix(i,2);
          resp=1;
      end
      i=i+1;
  end
end
```

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