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Abstract

The versatility of open source technologies could grant them an intriguing place in the industry. More particularly, an open source hardware automated guided vehicle (AGV) might show up as an ideal solution for low-scale logistic process, as well as a useful development and didactic tool. What is more, a modular vehicle with interchangeable components would comply even better with this philosophy. Hereafter, besides from a literature review including research related to the many subjects that this project attempts to orchestrate, an open source hardware methodology has been followed, a comparison analysis of each component and structure performed and configurations of possible AGVs selected, in order to shed light on the viability of conducting this sort of project in reality. Plus, a modular frame has been designed and tested with computer-aided and simulation tools. The conclusions show that constructing an open source-based industrial vehicle is to a high extent feasible, although the precise economic outcomes are not clear and building a real model is a future requisite to give evidence.

Certification

This thesis has been submitted by Miguel Gámez Berral and Miguel Martínez Lozano to the University of Skövde as a requirement for the degree of Bachelor of Science in Production/Mechanical Engineering.

The undersigned certifies that all the material in this thesis that is not my own has been properly acknowledged using accepted referencing practices and, further, that the thesis includes no material for which I have previously received academic credit.

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Miguel G: I would like to thank my mother for all the support she gives me to progress in my work and to reach my own goals. I am also grateful for all the effort and dedication of my colleague Miguel without him this would not have been possible.

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Nomenclature and Symbols

Standard referencing note: *although according to the norm the standards should be cited as (EN 2020), given that in this case the two most reviewed standards are from the year 2020 and created by the EN body, the full name of the standard (which includes the organization and the year as well) will be used in order to make reference to it, e.g. (EN 1175:2020), so as to clarify the reader's exertions.*

Nomenclature

AGV	Automated Guided Vehicle
AMR	Autonomous Mobile Robot
COF	Coefficient of Friction
CAD	Computer Aided Design
DoD	Depth of Discharge
EN	European Normative
GPU	Graphical Processing Unit
ISO	Internation Organization for Standarization
LiDAR	Light Detection and Ranging
Li-ion	Lithium Ion
LFP	Litium Iron Phosphate (Li-ion battery type)
µC	Microcontroller
NIC	Network Interface Card
NMC	Nickel Manganese Cobalt Oxide (Li-ion battery type)
OS	Open Source

OSH	Open Source Hardware
OSS	Open Source Software
PLC	Programmable Logic Controller
RADAR	Radio Detection and Ranging
RSS	Received Strength of Signal
RGBD	Red Green Blue Depth (camera type)
SLAM	Simultaneous Location and Mapping
SBC	Single-board computer
SONAR	Sound Navigation and Ranging
SHS	Square Hollow Section
SS	Swedish Standard
vSLAM	Visual Simultaneous Location and Mapping
WLAN	Wireless Local Area Network

Symbols (section 4.2.6 – Torque estimation)

a	Acceleration
F_{ad}	Aerodinamic Drag
COF	Coefficient of Friction
R	Gear ratio
g	Gravitational acceleration (9,81 m/s^2)
Gr	Grip force
m_{cart} (m_c)	Mass of the pulled cart
T	Motor torque
F_{cart}	Pulling force for the carts
ε	Rear axle : front axle weight distribution ratio
F_{rr}	Rolling Resistance
K_{rr}	Rolling resistance constant
F_{slope}	Slope-related force
F_{te}	Tractive Effort
$m_{vehicle}$ (m_v)	Vehicle mass (without the load)
r	Wheel ratio

1. Introduction

The fourth industrial revolution, in which automation plays a crucial role, is more than a mere conjecture nowadays. Factories all around the globe are starting to update their production paradigms so as to obtain more reliable and flexible systems. Making the factory-level processes independent from a human operator contributes towards enhancing the quality and safety standards for the operators, besides from the unquestionable production perks (Acemoglu 2019). Automatizing the logistic side is one of the most intriguing challenges in this day and age: there is a plethora of vehicles capable of independently accomplishing many different transportation tasks, fitting perfectly the brand-new industrial way of thinking (Theunissen 2018). The most typical forms of driverless industrial vehicle are Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs).

AGVs are unmanned devices generally designed for carrying loads, mostly used (excluding a few interesting exceptions, such as Serrano's (2018)) within industrial-like environments. According to Ullrich (2015), they have been used since the mid-twentieth century, but have undergone an exponential growth from the 1990s. This swelling of the AGV presence lasted roughly until the 2010s, when industries started to demand more customized models, causing the manufacturers of AGVs to create products aimed for more diverse sectors, becoming the current *status quo* (Ullrich 2015). Due to improvements in computational power and software, AGVs have evolved into more stand-alone, intelligent vehicles. This differentiation has been so wide they have been termed 'AMR' to distinguish them from the older devices. They are likely to become the new standard logistic solution in factories sooner rather than later (Köseoğlu et al. 2017). As this thesis is hardware-minded, they are going to be considered virtually equivalent.

One can find AGVs and AMRs of all sizes and purposes. In spite of all the differentiation, every European industrial driverless machine ought to fulfil not less than the proper European Norms (EN) legislation. Before summer 2020, the standard to follow for this kind of vehicles was EN1525 – approved in 1997 –, it was by then replaced by EN ISO 3691-4:2020 (*Safety for industrial trucks - Driverless trucks and their systems* 2021). This is quite relevant because the new standard is much more modern and suited for new technologies than its predecessor and could significantly impact the AGV market in the near future (Kidman 2020).

These regulations do not impose concrete design specifications. This means that as far as all the safety features are satisfactorily attained, the design and components are up to the manufacturer. Hitherto AGVs have been independently conceived and frequently not interoperable, which depletes their flexibility and accessibility. A more generalized model that can be readily modified would mean a stride forward in the development of automized vehicles. A quite interesting approach towards a standardized, affordable AGV could lay its foundation on the open source (OS) movement. The Open Source Initiative (2007) has defined OS as free-access, free-redistribution, undiscriminated, non-restricting code. The most well-known practice of OS is in open source software (OSS), i.e. source codes with any kind of varied purpose, which are ruled by the aforementioned principles, and can be found in online open platforms (e.g. github.com). Some illustrations of this are the libraries SciPy[1] for data science and TensorFlow[2] for machine learning. The focus of this thesis, though, will be on open source hardware (OSH): as with its elder brother, it is licensed-distributed and can be found unrestrictedly on the internet, but instead of being code, it consists of the detailed plans for given device, so that anyone can not only build but contribute to that hardware with modifications and adaptations of their own (*What is Open Hardware?* 2021).

1.1 Problem Statement

At present, AGVs and AMRs in the market are relatively costly (Table 1.1), so small and medium-sized companies are probably unwilling to take the financial risk of buying vehicles, and this lack of automation depletes their productivity and thwarts its competitiveness. There is a problem in profitably when automating low-scale processes – non-valuable material handling mainly (Feledy and Luttenberger 2017) – that do not especially require as much economic resources as current AGVs and AMRs demand. This could become a necessity that can be possibly filled by a more flexibly designed vehicle. Being able to freely access designs could lower the prices and open the AGV world to smaller companies, expanding their potential.

Table 1.1 List of AGV types and corresponding prices. Source: AGVNetwork (2021)

Type of AGV	Estimated price ($)
Automated Guided Cart	14,000
Towing tractor	30,000
AMR	30,000
Automated pallet jack	60,000
Automated forklift	80,000
Automated Very Narrow Aisle	150,000

The advantages could rely on its functionality too. To the day there is some secrecy surrounding AGV designs, so that the room for versatility is not as large as it could be, as it exclusively depends on the manufacturer alone. Public designs utilized in common by different manufacturers means more chances for doing updates that can boost the performance of the vehicle. Furthermore, it would constitute a more comfortable environment for innovation (Sheppard et al. 2018).

In this sense, having a disposable cheap vehicle that can be used as a development mule, i.e., as a testbed vehicle to evaluate certain prototype components (Martin 2017), provides significant support to speed up the progress of this technology. It would facilitate new devices, software and safety tests, given it wards off the construction of a thousand-dollar worth vehicle for testing purposes only.

Jumpstarting the design and implementation of an automated guided vehicle that can be suited for industrial applications and can additionally be adopted and enhanced, or having its functionality being narrowed down by anyone, could mean an enormous leap forward (Ghapanchi et al. 2014). Not only

[1] https://www.scipy.org/
[2] https://www.tensorflow.org/

for automated vehicles' sake and their development – having an open frame design could help unify them and make their progress more organized –, but also for the OSH movement, an industry-based contribution is something quite uncommon (Open Source Study 2021).

1.2 Aim and research question

The aim of this project, hence, is exploring the practicability of a legitimate, open-hardware Automated Guided Vehicle framework, industrially minded; that can be constructed with either smaller budget or better quality-price ratio than commercial AGVs, for an industrial or development context.

Sticking to an open hardware philosophy, designing a highly customizable vehicle (from frame to peripherals) will be a perennially concerning objective. This new industrial era could be the gate for OSH to start being significant, but there is a chance that it is too early for it to be affordable or sustainable, or simply OSH projects like this will find no place in the industry. However, having unbounded designs has clear benefits for industry and could help it grow to grant optimized and safe machinery. OSH could ideally become one of the new industrial pillars (Oliver 2018), and hence this topic needs to be addressed.

The issue to wonder about and bear in mind herein is the actual feasibility of doing an OSH industrial design of this calibre. There are definitely some OS industrial valid projects (Arduino[3], OpenPLC[4]), but they are software minded or of smaller components, that suit better the OSH picture this far. Therefore, a question to constantly consider and ultimately evaluate is: **is it possible to develop an industrial level, open hardware AGV given the hardware and software currently available?**

1.3 Sustainability aspects

The long-term effects of a project like this are hoped to be: a free-access, license-distributed industrial device. This is currently something rare but that could become the norm in the near future. Having an OS model available means that every industry willing to begin developing an automated vehicle will not be forced to start from scratch and would be able to dedicate its resources into developing a more sophisticated one, eventually allowing the field to evolve rapidly (Scacchi 2004) and encouraging a feedback cycle within the OSH framework, creating a closed-loop progress movement.

This would involve, in an ideal scenario, some socio-economic effects, as every form of technological advance does. In this particular case not in the technology itself, as no ground-breaking accomplishment will be carried out, but more of an advance in perspective, as once the developers of UNIX paved the ground for OSS, which led to huge achievements, this project could be a small step towards the big goal of ubiquitous OSH.

Lastly, an open platform can bring ecological perks, too. Waste is greatly decreased when a device is easily repairable, updatable or repurposed; in opposition to a classic, sealed one that may be either

[3] www.arduino.cc/pro/case-studies/idt
[4] https://www.openplcproject.com/

disposed of or returned. Even in the best of situations, in which the supplier could repair their vehicle, transportation must still be done. The optimal solution is being able to fix locally.

1.4 Overview of the thesis

Over the rest of this thesis, the development process of an OSH AGV will be described as thoroughly as possible, starting with a theoretical framework (Chapter 2), in which the less tangible aspects are shown; followed by a literature review (Chapter 3) of all of the relevant documentation and design procedure (Chapter 4).

Later on, resulting hardware configurations will be shown and classified (Chapter 5), along with a discussion and evaluation of the whole project (Chapter 6). Lastly, a conclusion summarizing the most crucial parts of the thesis and solving its main concerns (Chapter 7). The span of this thesis (excluding annexes, title, tables of contents and lists) is of 39 pages.

2. Theoretical Frame of Reference and Literature Review

When it comes to developing a full operating, autonomous vehicle, the theoretical side behind it becomes huge, as a great variety of fields need to be mustered and mastered. A thoughtful approach would separately contemplate the different fields applied to the diverse components of the AGV (Mettler et al. 2019).

Excluding Amsters and Staels' (2019) Turtlebot – education-minded – (Figure 2.1) and Ruben's (2018) M.U.L.E. – a follow-you load-handling non-industrial vehicle –, which fall a bit off from what this project intends to accomplish, there has not been a similar project to ours to compare with. Despite this there exists plenty of research on AGVs, as it will be shown, as well as on OSH, which even though may not provide any technical edge, will instead help adopt an OS perspective that must be in the vicinity all along the design process.

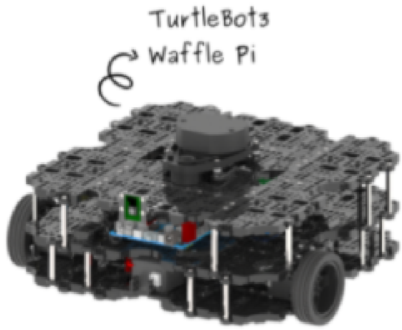

Figure 2.1 TurtleBot3 Waffle Pi. Source: Amsters, Staels (2019)

A literature review of several papers and sources was conducted using the databases *Google Scholar*, *Scopus* and *ResearchGate* and *Google* as search engine for each of the parts under research. The mustered information was posteriorly filtered according to the relevance to this project and among the scientific community. In other words, scientific articles have always been prioritized to other sources, and within these the ones with the more citations or better accuracy with the topic studied. There are, nevertheless, several websites and non-scientific sources that have been chosen for convenience's sake. The standards were facilitated by the University of Skövde.

2.1 Open Source

Open Source Initiative founder Eric Steven Raymond's casual text *The Cathedral and the Bazaar* (2000) represents a wonderful allegory on how to develop OSS which provides a strong starting point for the study of this approach. It evaluates the unique benefits of OSS and its methodology, opposed to the prior organised *modus operandi* of coding. Similarly, Levine and Prietula (2014) examine the capabilities of Open Collaboration in creation processes, even though open hardware is not mentioned explicitly, provides a deepened formal structure for OS development in general. Some implementations have come bound to the recent pandemic scenario: Pearce (2020) and Mora et al. (2020) pry the contribution of OS, 3D printed ventilators to cope with the high demand during tough times, deriving in some upbringing results.

2.2 General AGV knowledge

The AGV picture is solidly drawn in Günter Ullrich's guide *Automated Guided Vehicle Systems* (2015). Not only does it tell its history, but it additionally displays the different types of AGVs (See Table 2.1), mechanical parts, navigation and guidance, and safety standards, among other valuable information. Ullrich has been, in short, a base pillar of the project. Another, newer, AGV state of the art report by Feledy and Luttenberger (2017), builds on some extra aspects of interest.

These reviews explain in detail almost every type of existing AGV, easing the process of choice of the kind of vehicle to develop; in addition, a general outline of the principal components, i.e., battery, motor and brakes, chassis and wheel configuration; is depicted. Moreover, they also showcase the required safety measures that must be included to accomplish the industrial requirements (emergency stop button, signalling, brakes, plates, sensors…). These are all key aspects to consider when designing any industrial device, being polestars during the first stages.

Historically, the first models of AGV consisted of industrial vehicles tweaked to be automatically steered, with bumpers that made them stop safely. Later on, owing to advances in electronics they were modernized with improved sensors and onboard PLCs as processing units to allow them to be independent means of transport. Currently, although some vehicles are still manufactured by automatizing an existing one, most of the models sold are conceived as an autonomous device from the first stance (Table 2.1), particularly if they do not carry exorbitant amounts of weight (Ullrich 2015). Since this project proposes an open design for a modern AGV, it will necessarily be of this second type.

Table 2.1 Categories of AGVs. Adapted from Ullrich (2015)

Designation	Load	Description
Forklift AGV	Pallet	Floor-level load pickup, various heights, standard or special pallets or other fork-compatible containers, stackable, typical payload: 1 t. Can be specially designed or adapted
Piggyback AGV	Pallet	Usually limited to one transfer height, side load pickup using roller tracks or chain conveyor, typical payload: 1 t
Towing vehicle	Trailer	"Tugger". Pulls multiple trailers, typical total weight of trailers: 5 t
Underride AGV	Roller container	The standard AGV in such places as hospital logistics. It underrides the roller container, and lifts it for transport. Typical payload: 0.5 t
Assembly AGV	Assembly object	Use in serial assembly, a substructure holds the pickup for the assembly object. Typical payload: up to 1 t
Heavy-load AGV	Rolls, coils	Transporting heavy paper rolls or steel coils up to 35 t
Mini-AGV	Small Load Carrier	Use in large fleets, e.g. for commissioning
PeopleMover	Passengers	For conveying passengers, similar to small or large buses
Diesel AGV	Diverse	Outdoor vehicles, usually diesel-electric or diesel-hydraulic drive. Typical payloads ≥3 t.
Special AGV	Diverse	Special solutions for special tasks. All AGVs that do not fit one of the above categories

To build an entire Automated Guided Vehicle, as with any kind of electronic device, a structural frame, mechanics, hardware and software are required (Feledy and Luttenberger 2017). The scope of this project is creating a modular, editable frame that can hold several distinct hardware components and, as a consequence, support varied software components and enable wide variations in behaviour.

2.3 Component analysis

Diving into more up-to-date and specialized documentation, a component, structure and standard walk-through is more than adequate. Firstly, finite element analysis insights will play some role in the fabrication of a legitimate frame. Finding the most suitable structure (both shape and material) without having to oversize and waste material, will grant better performance (Figure 2.2). Some physics notions will show usefulness too with the mechanical architecture, namely motor, reduction and wheel choice, so that this AGV is able to generate the necessary torque and speed. Concerning these (structure and mechanics), few scientific literature has proved useful, so informative websites and physical and logical-empirical criteria have been utilized.

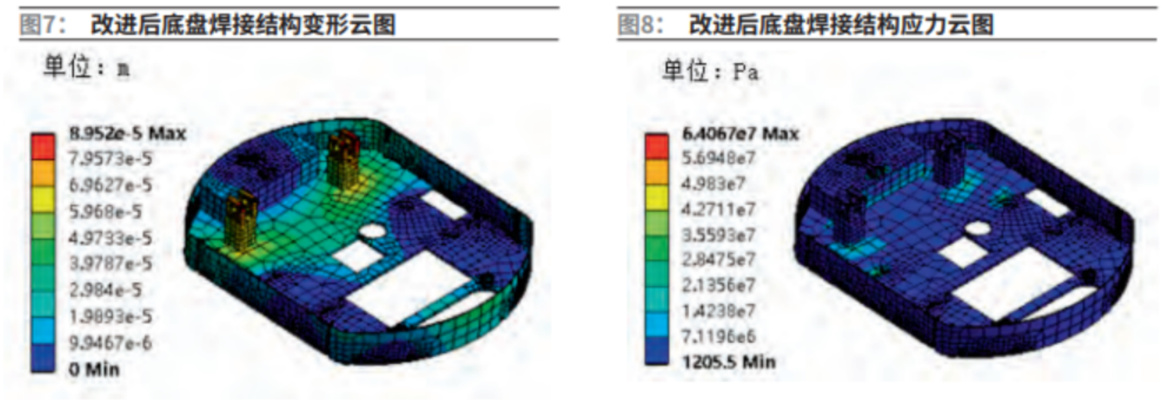

Figure 2.2 Finite element analysis of AGV frame. Source: AGVBA (2020)

Serrano (2018) describes a solution suited for an airport underride AGV, with all of the component choice and structure design. Similarly, Cheira (2019) comes up with a material handling AGV, doing some emphasis on the structural side of the vehicle that has inspired the torque calculations performed. Lamy (2016) explains and proposes different mechanical designs, performing a thought-provoking analysis about omnidirectional (Mecanum) wheels in AGVs (Figure 2.3). These three reports are truly relevant when it comes to defining the frame dimensions and wheel distribution of the vehicle, not forgetting the mechanical base, both theoretical and practical.

Figure 2.3 Meccanum-wheel AGV model. Source: Lamy (2016)

The vehicle and its components will be electrically powered by a battery. The battery choice knowledge leans on the study by Stenzel et al. (2014), that compares and evaluates several features of different relevant storage systems, including Lead-acid batteries and most of the types of Lithium-ion cells. An article by the website Battery University (2020) also makes things clearer about Li-ion batteries. Among the most used ones, lead and lithium ion can be remarked as the most profitable ones, owing to their performance to price ratios. They are the most common among the market as well (AGVNetwork 2021). The final choice can be influenced by aspects such as price per energy unit, cycle life or Depth of Discharge (DoD) – in other words, which percentage of battery is consumed in each discharge – (Figure 2.4). Recharging schemes will be an important consideration as well, they directly affect the working availability of each vehicle.

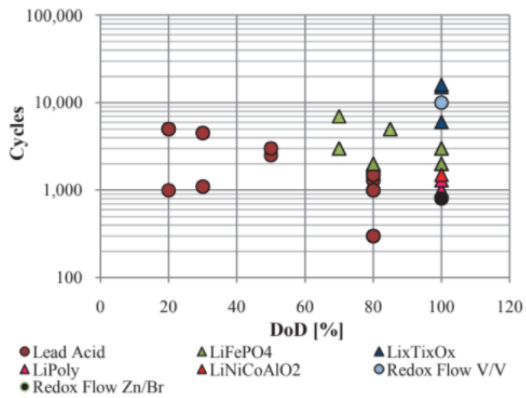

Figure 2.4 Cycle life vs. depth of discharge (DoD) of different batteries. Source: Stenzel et al. (2014)

The processing burden of the vehicle will ideally rest on a Programmable Logic Controller (PLC), a processor secured for industrial applications, or equivalent unit: lighter versions could make use of conventional microcontrollers and more sophisticated ones of Single Board Computers (SBCs). They will account for all of the signal processing except telecommunications. There is not much literature here excluding the aforementioned guides (Ullrich 2015, Feledy and Luttenberger 2017) that introduce the topic of signal processing and fleet management, and catalogues setting several models of boards.

The frame ought to be designed to have a range of sensors equipped depending on the manufacturer's choice, being LiDAR (Light Detection And Ranging) the most recurring one (Figure 2.5). Wang (2020) portrays in a conference the use of sensors in AGVs and AMRs, evaluating their different pros and cons. In cases which a vision system is applied, a graphical unit, called GPU, is fundamental for a swift multi-task management (Abel 2020). The telecommunications are regulated via a Network Interface Cardboard (NIC) bridging the vehicle and the computer which externally controls it.

On the programming side, that is to say, the software controlling the driverless vehicle, plenty of researchers contemplate an extremely wide range of algorithms and teleoperation methods. Oyekanlu et al. (2020) mention some of the most recent advances on the field and gives a clear explanation of the current state of AGV and AMR operation. At present most of the academic background material to AGVs actually focuses on the algorithmics behind location, navigation and fleet scheduling. This report is aimed mainly for the design of it, i.e., the goal is to make the design modular, thus the mindset is creating a vehicle frame in which anyone could run their own preferred algorithms; no deep study on the software shall be done.

However, it is worth mentioning that on a regular basis the sensor data is filtered down to keep the trajectory, which is *per se* calculated mathematically (generally graph theory) and assigned by a software that embraces the whole AGV fleet behaviour, in order to coordinate movements.

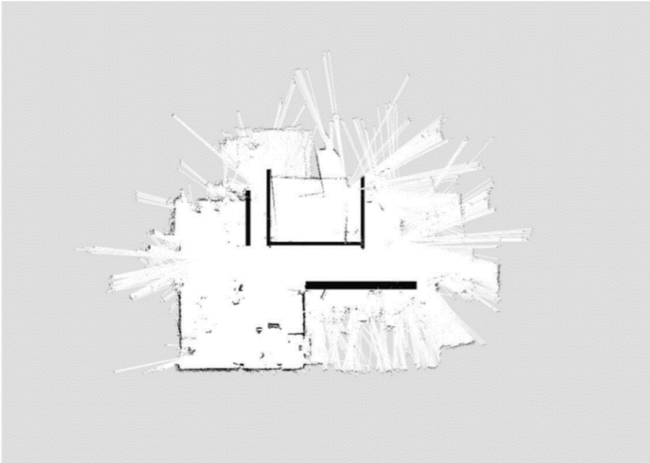

Figure 2.5. Map of an installation using LiDAR and SLAM algorithms. Source: Dzezhyts (2020)

2.4 Standard information

Industrial devices require standardization as a safety and performance warrant. Each standard is constituted for a concrete device or set of devices as a rule, although there are exceptional standards to evaluate definitions and concepts. Which standard is accepted depends on the where: ISO standards are worldwide whereas EN or DIN European, ANSI or NEMA American, or national scale like UNE or SS. As the reader may have inferred, the national standards have to be in accordance with the continental which will simultaneously follow the worldwide one; thereby the most restricting and ones that will be looked upon are the national standards.

The current standard is ISO 3691-4:2020 (SiS 2021). It discusses the requirements a given operational driverless truck should meet to be considered valid for industrial environments. More particularly it references other ISO, EN, and IEC standards for elementary safety regulations (electrical components and machinery), and some other more complex demands such as stability, performance level and the listed safety mandatory measures, as well as instruction on signalling, warnings and added documents. It annexes, besides, several chapters that discuss several secondary issues, namely the normative regarding operating areas, hazards, rated capacity, load transfer and some verifications tailored for the manufacturers (Kidman 2020, EN ISO 2020).

Other standards are EN ISO 13849-1:2015 (2015), which categorizes any given safety measure in performance levels (PL), given the risk in which they can put the operator – these PLs will set the least concerns for each vehicle component –; and EN ISO 1175:2020 (2020), which deals with the electrical and electronic safety measures regarding industrial trucks, involving power source, motors/electromagnetic devices, and electrical connectors.

2.5 Method

This work covers the creation of a vehicle, all creative processes ought to go under a methodology sustained by design science research. Hóvarth (2007) and Peffers et al. (2017) display this creation process, and Pello (2018) interestingly summarizes the most relevant contributions to this discipline. The chosen method to follow, though, is the one specifically aimed for open hardware designs by Oberloier and Pearce (2018).

The process of creation of the OSH AGV will be split in two main blocks. Firstly, the generalized method that will be implemented will be detailed. Secondly, this process will be executed towards the concrete solution needed (in following chapter). According to Oberloier and Pearce (2018), the creation process to develop an OSH application ought to involve five main steps that can shortened as follows: Review and Problem Description, Design, Validation, Documentation and Sharing. Those actions are conveniently executed and iterated to conform the overall design (Figure 2.6).

Figure 2.6 Diagram of the open hardware design procedure.

2.1.1 Review and Problem Description

Earlier in this paper, the first of these five actions has been already fulfilled. Extensive literature has been analysed and similar solutions studied. Furthermore, the necessities this project targets have also been defined and the problem has been encapsuled within precise boundaries.

2.1.2 Design

The succeeding move, and most principal concern of this thesis, will be designing a solution for the method of creation that is supported by scientific research or deductions. In order to properly create an open hardware design, the principles outlined below must be addressed agreeing to Oberloier and Pearce (2018). They are key factors in bringing the design as close as possible to the objectives of the Open Source Initiative (*The Open Source Definition* 2007).

- Use only free and open-source software tool chains and open hardware for the fabrication of the device.
- Attempt to minimize the number and type of parts and the complexity of the tool.
- Minimize the amount of material and the cost of production.
- Maximize the use of components that can be distributed digitally manufactured from using widespread and accessible tools such as the RepRap 3D printer.
- Create parametric designs with pre-designed components, which enable design customization.
- All components that are not easily and economically fabricated with existing open hardware equipment in a distributed fashion should be chosen from off-the-shelf parts, which are readily available throughout the world.

2.1.3 Validation

The resultant design shall undergo a validation process, in the sense that it satisfactorily solves the problem it is destined to cope with. If the validation proved the design insufficient, it would unavoidably need to be reformulated again. As no real model is being constructed, these validations are purely theoretical, by means of physical calculations, CAD tools or simulations. How flexible the resulting AGV becomes is quite important as well. The validation is trimmed nonetheless, in such a way that it would not be complete until it is tested in the real world. The goal of this project is, in this sense, unfinished.

2.1.4 Documentation

The convenient CAD files, reports and other files involved will be gathered and polished lest inaccurate or irrelevant information is left. It is crucial that all of the displayed information is clear and concise for anyone willing to adopt the project. Otherwise, the designs efforts would be futile.

2.1.5 Sharing

The outcomes and technical documentation and files concerning this solution will be publicly available through DiVA and GitHub.

3. Implementation

3.1 Configuration choice

The criteria to decide the several configurations have been boiled down to the different ones that influence the choice of components. For instance, the AGV being industrially prepared is decisive, as it makes hardly any sense building a vehicle out of both industrial and non-industrial parts, given the first are reasonably more costly. Load capacity, complexity and performance are the magnitudes on which the AGV design shall depend. Subsequently, whereas the device being industrial is a binary choice, the remaining are less obvious. One of the uncountable ways to make the classification is creating a separated table for the requirements each load interval imposes, and a plot that displays complexity and performance. Each point in the plot could be then colour-highlighted as industrial or vice versa. The scales of complexity and performance, despite relying on what has been stated in the following component research, will be arbitrary, as they are relative to each component (Figure 3.1).

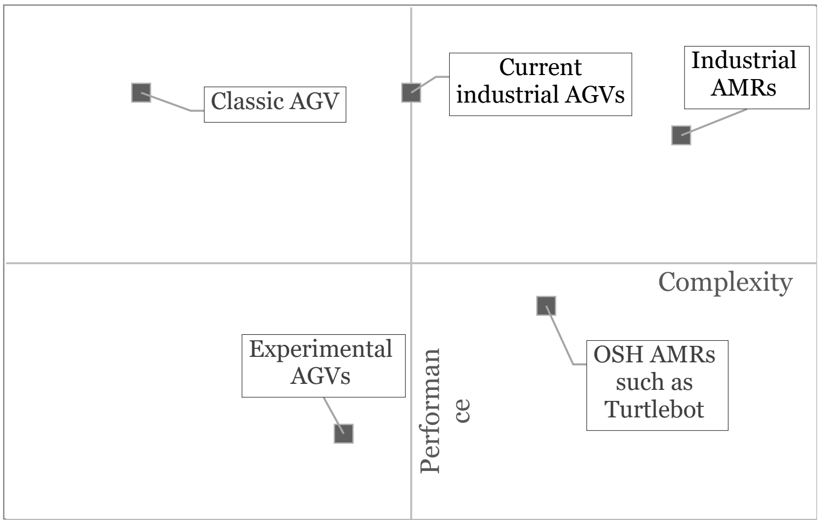

Figure 3.1 Plot classifying arbitrarily material handling vehicles. Complexity increases towards the right of the chart and performance towards the top.

It may be remarked that the several configurations chosen are generalized versions and, down to the modular nature intended, any desired vehicle can almost be built. More ambitious or off-the-charts versions could be thought of because of the modularity.

3.2 Design

The main development phases in the AGV have been chosen to conform a several-stage process that starts on the most fundamental issues of vehicle building and goes through most of the technical specific aspects. Therefore, the vehicle type and structure will be dealt with first, followed by the analysis of the battery and mechanics and concluded shedding light on the rest of more variable, less influential components. With the aid of the CAD software Autodesk Fusion 360, a model of the vehicle will be designed.

3.1.1 Vehicle type choice

Owing to the size and scope of this project, the mass the vehicle will carry will roughly be of half a ton (500 kg). Heavy load trucks, piggyback (prepared for larger loads) and mini AGVs (smaller loads) are off the point and hence to be discarded. Automated forklifts may require an excessive amount of research and difficulties concerning load transportation and automation if they are designed from scratch. Consequently, the two remaining types are the underride and the tugger (See Table 2.1). Due to their similar structures, a wheel configuration that suits both types would be desirable. In this case of study, a tugger that can work as an underride (or as both) will be targeted to provide as much freedom to the functionality and design as possible, building bridges toward future modifications and reformulations by the OS community, and the transition from our model to a pure tugger or a pure underride were as effortless as possible.

Another factor to consider is scalability. The design parameters must ideally be easily enlarged or dwindled depending on the manufacturer's intention. If performing all the research procedure again were required to scale the vehicle up or down, the design would not encompass an OSH guiding example.

The chassis layout has been chosen with the following needs in mind: high traction capacity for towing, which means that the highest possible percentage of weight must be on the driving wheel(s); and the need for stability, as we will also be carrying cargo on top of the AGV and this would compromise stability if not taken into account. A number of objectives have also been set, which lie in the simplicity, compactness and low cost of the chassis format.

To meet these requirements, the most optimal option has been a 4-wheel base, the two rear wheels being independently driven and the two front wheels casters. This arrangement also defines the type of steering, which must be differential (the direction of the vehicle is controlled by the speed difference between the two driving wheels). In this way, it is possible to have most of the weight of the robot supported by the two driving wheels, and still have more than enough stability due to the two separate supports instead of having for example only one driving wheel (Figure 3.2). Furthermore, as there is no mechanical steering system, the goal of simplicity in the installation is achieved and the manufacturing cost is also reduced. The robot will also be able to rotate in its place.

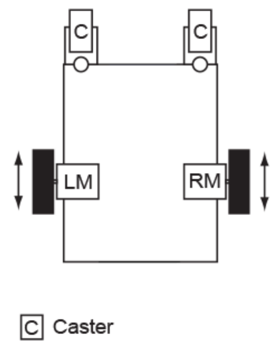

Figure 3.2 Wheel disposition diagram. Source: https://www.roboteq.com/applications/all-blogs/12-robocart-ultra-low-cost-agv-demonstrator

A possible flaw is that, from the programmer's viewpoint, configuring differential steering is a tougher task than simply having a steering mechanism that directly generates the output. Besides, having two motors instead of one may increase costs.

3.1.2 Frame – size estimation

In order to find the size of the vehicle frame the principal components (battery, motor, transmission, wheels…) size should be delimited. These will rely on the payload to carry or pull, speed and range. This appraisal will lean on other similar existing models. In order to allow modularity, the largest size possible for each component will be considered, so a wider variety of parts can be used. Once demarcated, computer aided design (CAD) models are going to be carried out. Finite element analysis will evaluate the validity of the frame, leading to an iterative process that concludes with an optimal frame.

3.1.3 Battery

The electrical supply will be one of the most relevant parts of the vehicle, because it defines a great share of the price, weight and volume of the vehicle. Furthermore, battery life is key when deciding a suitable fleet strategy and size. Choosing the best type of battery is crucial in order to utilize the working times and discharge of the battery. Chemistry selection relies on several variables, a roughly generalized decision process is shown below (Figure 3.3). Although Ullrich (2015) suggests that Lead-acid and Nickel-Cadmium are the most recurring chemistries, Lithium-ion represents a much more interesting option than Ni-Cd (Feledy and Luttenberger 2017). Among the several types of Li-ion, Lithium Nickel-Manganese Cobalt Oxide (NMC) and Lithium Iron Phosphate ($LiFePO_4$ or LFP) have wider use (Stenztel et al. 2014) and will be the ones considered.

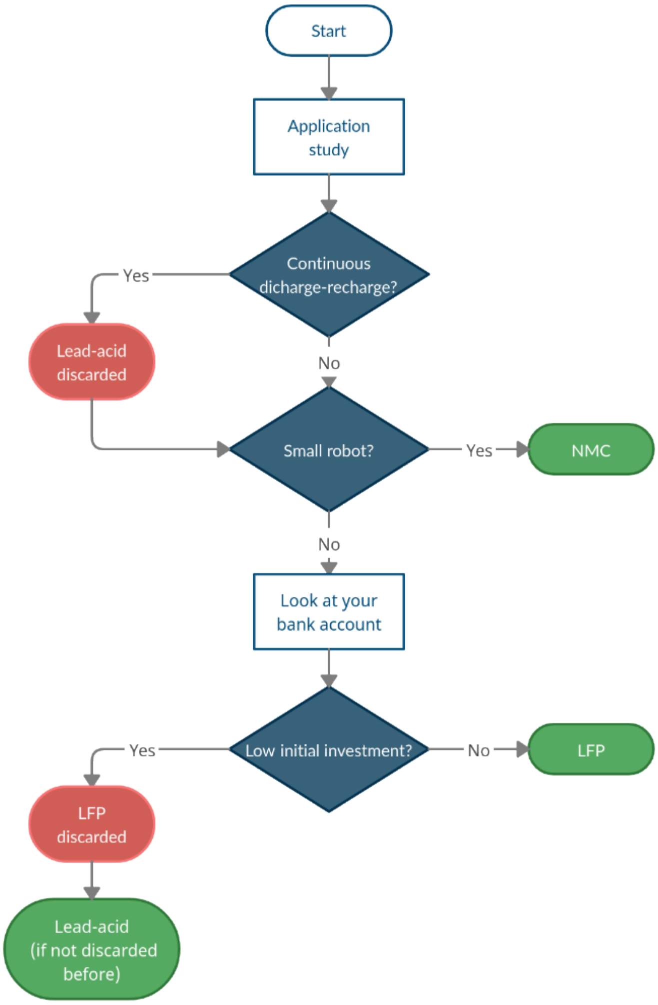

Figure 3.3 Flowchart showing a recommended battery choice process.

One determining issue is the recharge schedule: the AGVs could either operate during regular shifts, and recharged overnight, or be continuously charged and recharged. In the latter case, quick charge becomes essential, and therefore Lead-acid is not suitable (Feledy and Luttenberger 2017). In the instances where the AGV size was reduced, energy density is prioritized, thus NMC is one of the safest options (*BU-205: Types of Lithium-ion* 2021). Economically speaking, LFP costs are higher than NMC and Lead-acid, which may discard this solution in low-budget projects.

Other parameters including weight, safety, life span (*BU-205: Types of Lithium-ion* 2021) or CO_2 mass emitted per energy unit during production (Baumann 2017) can help clarify the decision. Plus, if it were to be built from separate cells (instead of directly purchased), it is worth mentioning that li-ion requires a Battery Management System, which could make the process more complex than using lead-acid. OSH Battery Management Systems exist[5], if an utterly DIY battery version is looked for (Figure 3.4).

[5] https://foxbms.org/

If doubt still arises, or just the most profitable cell is sought, a ratio of energy by cost and cycle can be calculated – not only the watts per dollar matter, but also the cycles that each type of cell can withstand, with long-standing interests –, based on an optimal depth of discharge (DoD). Certainly, battery life is affected by how deep it is used (Stenztel et al. 2014, *How to prolong lithium-based batteries* 2020); a larger battery would imply a lower DoD for the same application (hence a longer life), although a greater initial price. As a result, an optimal DoD may be calculated (See Annex A2), and the price ratio derived for all of the battery types. It turns out that **LFP (17.6 $/kWh cycle)** and **lead-acid (15.6 $/kWh cycle)** have similar ratios, making them similarly long-term profitable, whereas **NMC (25 $/kWh cycle)** figures fall off their peers' marks, discarding it as a valuable option. Although considerably more expensive in the long run, the great advantage of the NMC battery is its energy density (approximately doubles the LFP), making it the best choice if space optimisation is required (*BU-205: Types of Lithium-ion* 2021). Yet, li-ion costs are gradually decreasing, consequently these rates could easily change in favour of LFP and NMC in the upcoming years.

The three kinds of battery do not interfere against EN ISO 1175:2020, as long as they fulfil safety functions, such as electrolyte isolation, and fire, water, dust and leakage proofing (the latter in the case of lead-acid). Still, probably the most efficient option is purchasing the batteries from an industrial manufacturer instead of trying to build one or acquire a non-industrial one, when the vehicle is destined to roam around a factory.

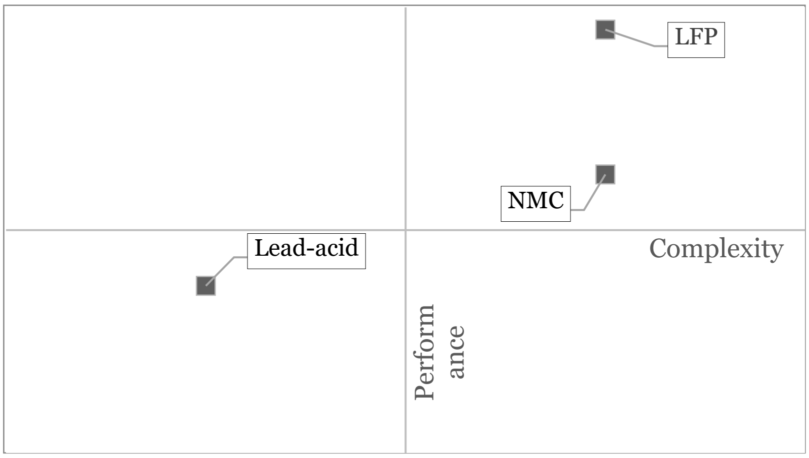

Figure 3.4 Complexity-performance battery type chart (top right corner represents highest complexity and performance)

To obtain the battery energy similar examples have been reviewed (See Annex A3) to take references: manufacturers suppose alleged 8-hour shifts and similar applications suggest that around 900 Wh of energy capacity are needed, which will become a target. The DoD they use is not mentioned nevertheless, so an energy estimation cannot be fully accomplished. Still, the largest battery that can fit will be looked for, given that generally a lower DoD will imply a higher long-term profitability. Thus, a 50% extra capacity has been adopted (around 1350 Wh or beyond if possible). To CAD-model it, lead-acid is regarded as the largest in size (less dense) possibility, namely four Vision 12V, 33Ah cells[6] that account for 1584 Wh will determine the peak volume of the battery compartment (Figure 3.5).

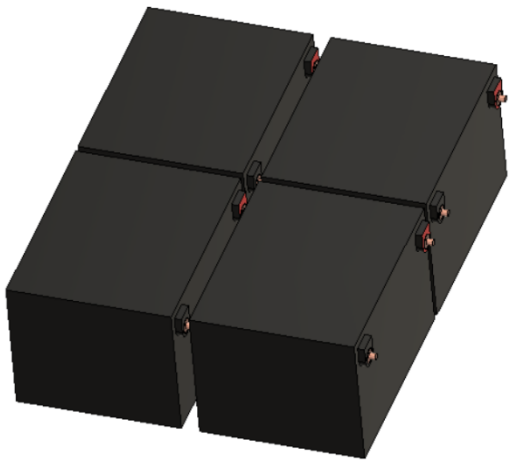

Figure 3.5 Battery compartment

3.1.4 Mechanics – Driving System

AGVs are machines principally destined to carry enormous amounts of weight at low speeds (EN ISO 3691:4-2020), hence the mechanisms and drives selected must comply to suit a high-torque, low speed application. Scalability is crucial too, in such a manner that a different behaviour, or simply a higher or lower output may be effortlessly implemented. It is worth recalling that all of the mechanics and traction solution is aimed for the rear axle exclusively, as there will be some caster wheels in the front end of the vehicle.

The easiest to implement and most effective (albeit most expensive) option is to use a commercially available integrated system, incorporating all the necessary components: motor, transmission, wheel, fail-safe brake and encoder. There are more compact systems, incorporating a wheel-hub-embedded motor and transmission, known as wheel hub drives, which can be considered the highest performance option. The main advantage of using such a system is that it will be certified by the company that manufactures it, thus ensuring its reliability. Furthermore, they are very compact and highly optimised systems, which can influence the size and efficiency of the AGV. The downside is that the modularity and flexibility of the components used is lost, and of course the designs of these commercial solutions[7] are not OS.

On the other hand, the option most in line with this project is integrating the drive system into the OSH paradigm. In this way, it is possible to obtain a solution that satisfies the objectives of modularity and flexibility that promote OS, so that the optimal components can be used in each specific case. Off-

[6] https://www.batterinet.se/shop/elscooter-batteri-12v-1849p.html
[7] https://www.wittenstein.co.uk/products/servo-systems/integrated-system-solutions/cyber-itas-system-for-automated-guided-vehicles-agv/; https://www.lafert.com/eng/products-detail.php?id=69&id_cat=23

wheel mechanisms (belts, chains and gearboxes) provide a much higher configurability and a lower price, without depleting mechanical output much (Hellinger 2019). The latter will be the selected option, thus. Belts and chains are the ones that make the mechanics slightly more modular and come at lower prices (Table 3.1).

Table 3.1 Benefits of economical off-traction solutions

Belt and pulley	Chain and sprocket
Low noise and vibration	More robust
Economical	High speeds

Belts bring better price, efficiency, shock absorption and noise reduction (Warner 2017); which place them above chains in this case of study, which on the other side can move at higher speeds and live longer (Warner 2017). High Torque Drive (HTD) belts are the ones chosen, given the relatively elevated forces utilized, even though there exist better performing profiles such as STPD or RPP (Erickson 1987), which come at higher costs. Gearboxes would be an intermediate option to consider between belts and chains and wheel-hub drives. They are a well-responding off-wheel solution that come at a cost in between hubs and belts/chains (Hellinger 2019). In either case, they can be relatively easily switched between, because the installation is identic (in the end it is either a pulley or a sprocket into the shafts).

A possible interface between shaft, wheel and belt pulley is a double flange hub (Figure 3.6) working as an interface between the wheel, shaft and belt pulley. Those hubs are principally employed in quads and karts, they are particularly useful because they can support any kind of wheel and belt pulley diameter, as long as they can meet the hub size, enabling modularity. This solution involves a motionless shaft connecting the rear wheels. Its main downside it brings is the lack of a place for an industrial brake, that may require a shaft to operate. On the whole, this is a mechanism for a non-industrial vehicle.

Figure 3.6 Double flange hub with bearing. Source: https://www.bmikarts.com/Double-Flange-Wheel-Hub-with-4-516-Bolts-on-a-2-1316-Circle-Includes-58-Bearing_p_1651.html

If the shaft was mobile, the powertrain should consist of two of them (left and right, so as to permit differential steering). In this situation the belt pulley and wheel are connected to the shaft with keys to transmit the torque between the components, and the shaft is attached to the frame with bearings. This is a much more preferable outcome than soldering them together, which would totally ruin modularity and maintenance. The shafts used in either case are rather mechanized to ensure precision and alignment. This would lend some space in the shaft for the fail-safe brakes to work, bestowing perfect validity for industry.

3.1.5 Mechanics – brakes

The EN ISO 3691:4-2020 standard specifies that the vehicle must incorporate a fail-safe brake, which must be activated in the events of emergency or the robot's power supply becoming cut off. The system shall be able to stop the AGV, even if the AGV suffers an electrical problem and power losses, for instance, if the battery fails. Notwithstanding, it should be noted that the motors are sufficient to decelerate the vehicle (and even take advantage of regeneration strategies if the controller allows it), so the brakes are only needed to fulfil safety requirements in emergency cases.

There are several solutions on the market for this problem, as it is a common requirement in equipment such as robotic arms or cranes, where the ability to fix a joint or stop a steel cable in the absence of electricity makes it an ever-transcendent necessity to ensure the safety and control of the machine (Dragone 2018). The option that best meets the needs of the AGV is a spring-applied electromagnetic brake, which consists of a friction brake engaged by a spring and released by an electromagnet (Figure 3.7).

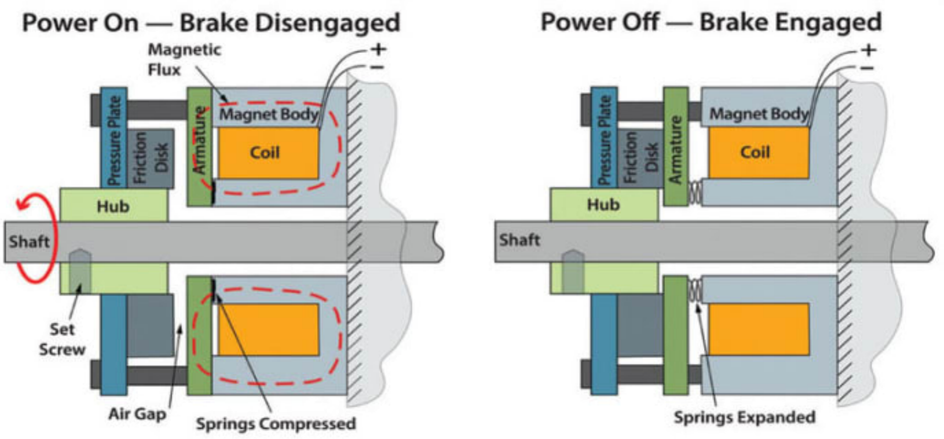

Figure 3.7 Spring-applied electromagnetic brake. Source: Dragone (2018)

Initially, the option of implementing an open hardware brake was considered, but it runs into several conflicts. There is at present no OS design of such a brake that could be incorporated, and the developing of one is beyond the capabilities and scope of the project, as it is a safety-critical device that must pass exhaustive tests and verifications to assure the reliability of the component. Once the OS option has been discarded, it is clear that a brake developed and certified by another company must be used.

Most brakes on the market follow a design which is conceptually the same as in Figure 3.7. Therefore, the only variables to consider are the torque required (which are found in the torque calculation section), size, power consumption and chassis fixture.

3.1.6 Mechanics – Torque estimation

The minimum force necessary to carry the load shall be inferred based on Cheira's (2019) calculations on a material handling AGV. Afterwards, the minimum torque needed (the worst of cases) will be deducted by multiplying this traction force by the wheel radius and dividing by the number of traction wheels to select the most appropriate motor and transmission without over-dimensioning. Grip is extremely significant as well. If the force at which the vehicle is pulled (known as **tractive effort** from now on) exceeds the grip of the wheels, they are going to slide and the vehicle will lose control. It is fundamental thus that this does not occur. Cheira (2019) defines tractive effort as the following sum of different forces (Figure 3.8):

$$F_{te} = m_{vehicle}a + F_{rr} + F_{ad} + F_{slope} + \sum F_{ext,x}$$

Figure 3.8 Tractive effort. Extracted from Cheira (2019)

Where $m_{vehicle}$ is the mass of the vehicle, a its acceleration, F_{rr} the rolling resistance, F_{ad} the aerodynamic drag, F_{slope} the added or subtracted force generated by the steepness of the ground, and the remaining term constitutes the sum of the remaining external forces. To make calculations simpler, the aerodynamic forces are going to be considered null (as the AGV is moving at very low speeds) and the slope null, a flat surface is supposed. The only external force is the pulling of the cart.

Cheira (2019) shows a peak rolling resistance of roughly less 4 % of the total weight of the AGV (lighter loads show a F_{rr} of 2 of 3%), so this value can be assumed as the rolling resistance constant (K_{rr}), providing that it will hardly ever be surpassed, simplifying this calculation (Figure 3.9).

$$F_{rr} = K_{rr} \cdot m_{vehicle} \cdot g$$

Figure 3.9 Approximate rolling resistance formula.

The effort the cart generates can also be written as the sum of the cart's rolling resistance and the product of mass and acceleration (Figure 3.10):

$$F_{Cart} = m_{Cart} \cdot a + F_{rr} = m_{Cart} \cdot (a + K_{rr} \cdot g)$$

Figure 3.10 Pulling force for the carts.

The vehicle mass is estimated in Annex A3, the cart mass will be the payload (max.: 400 kg) and the speed, acceleration and deceleration figures have to be approximated. A proper speed would oscillate around the 1 m/s mark, fast enough to rival an operator but not as quick as to create mayor damages in case of accident. A proper breaking acceleration would be of at least negative one m/s^2 second, to ensure the AGV is fully stopped after one second's time and fifty centimetres of distance. On the other hand, the acceleration does not need to be so demanding, any acceleration around 0,5 m/s^2 could be acceptable. For the given calculations, a 0,7 m/s^2 value has been selected.

Grip is the product of the normal forces by the coefficient of friction (COF) (Figure 3.11). The dynamic coefficient (the wheel is sliding instead of turning) is the one wielded, so that the minimum grip is withdrawn, as the static COF is always larger in value. The most common wheel material is polyurethane (*Wheel hub drive for automated guided vehicle systems* 2021), and the most basic floors are usually made of concrete (Lacoma n.d.); based on the research carried by Sonawane (2015) and Ranganathan (2015), the smallest – and considered – dynamic COF between these two materials is of 0,7.

$$Gr = COF \cdot m_v \cdot \varepsilon \cdot g$$

Figure 3.11 Formula for grip, where ε is the weight distribution between the two axes.

As the traction looked for is the rear axle one, the mass considered would not be the entire mass of the vehicle but the section that falls on the mentioned axle. A quick estimation, taking into account the batteries and motors would be on this side of the AGV, would suggest that around three quarters of the vehicle mass are resting on it.

A handful of cases must be thought of, and the forces and grip calculated and compared for each and every one of them (Table 3.2). The situations under scope involve carrying or not the 100 kg payload on top of the vehicle and using heavy Lead-acid or light LFP batteries, adding up to a total of four cases. As the aim is evaluating the grip, the worst case is being modelled, that is to say, the largest payload possible is going to be tugged.

Table 3.2 Comparison between grip and tractive effort for different situations.

	Load	m_v (Kg)	m_c (Kg)	F_{te} (N)	Gr (N)
Case 1	Lead Battery, loaded and cart fully loaded	240	400	698,88	1234,8
Case 2	Lead Battery, empty and cart fully loaded	140	400	589,68	720,3
Case 3	LFP Battery, loaded and cart fully loaded	210	400	666,12	1080,45
Case 4	LFP Battery, empty and cart fully loaded	110	400	556,92	565,95

Table 3.2 shows that the grip is in every case greater than the tractive effort, meaning that the wheels are not going to slide in any context, providing the initial conditions (no slope). Either way, the safest option so as to ensure a proper grip is to use the tugger as an underride. In another trend, the limit cart weight before losing traction can be found and different loads established for each case. The inequation to satisfy comes as follows (Figure 3.12):

$$Gr > F_{te}\,,\ hence$$

$$COF \cdot m_v \cdot \varepsilon \cdot g > m_v \cdot a + K_{rr} \cdot m_v \cdot g + m_C \cdot (a + K_{rr} \cdot g)$$

Figure 3.12 Inequation to find the maximum cart mass available.

Every coefficient is of Figure 3.12 is known except the mass of the cart, thus when the values are substituted and the inequation solved (Figure 3.13):

$$m_c \lesssim m_v \cdot 3{,}7115$$

Figure 3.13 Mass cart limit not to lose grip, depending on vehicle mass.

If the values are truncated to a multiple of 50, in order to lend some safety interval as well, the resulting load limits are the following (Table 3.3):

Table 3.3 Max loads for each AGV type.

	Load	m_c (Kg)
Case 1	Lead Battery, loaded and cart fully loaded	850
Case 2	Lead Battery, empty and cart fully loaded	500
Case 3	LFP Battery, loaded and cart fully loaded	750
Case 4	LFP Battery, empty and cart fully loaded	400

As the sought magnitude is the torque of the motors, it must be calculated multiplying the tractive effort by the wheel radius (torque is the product of force by distance) and dividing by the number of traction wheels (there would be one motor in each rear wheel). The transmission ratio of the belt (roughly 10 to 1) has to be included too (Figure 3.14). The wheel diameter is another facet: the smaller the radius the less torque needed but the more rolling friction. As the torque is feasibly met by employing a higher transmission ratio, a relatively high diameter (around 20 cm) is recommended so as to diminish the rolling friction and stress to the wheel.

$$T = \frac{F_{te} \cdot r}{n \cdot R} = \frac{F_{te}(m_v, m_c) \cdot 0{,}1}{2 \cdot 10}$$

Figure 3.14 Torque calculation, where r is the wheel radius, R the gear ratio and n the number of traction wheels.

If the tractive efforts of table 3.2 are reckoned, the resulting torque figures will be the following (Table 3.4):

Table 3.4 Motor torque needed to pull 400 kg load in each case.

	Load	T (Nm)
Case 1	Lead Battery, loaded and cart fully loaded	3,49
Case 2	Lead Battery, empty and cart fully loaded	2,95
Case 3	LFP Battery, loaded and cart fully loaded	3,33
Case 4	LFP Battery, empty and cart fully loaded	2,78

Analogously, when the tractive efforts are inferred from table 3.3, the resulting torque values come as follows (Table 3.5):

Table 3.5 Motor torque needed for each case carrying its maximum load.

	Load	T (Nm)
Case 1	Lead Battery, loaded and cart fully loaded (850 kg)	5,95
Case 2	Lead Battery, empty and cart fully loaded (500 kg)	3,49
Case 3	LFP Battery, loaded and cart fully loaded (750 kg)	5,24
Case 4	LFP Battery, empty and cart fully loaded (400 kg)	2,78

In short, **a heavier AGV will be able to carry more weight, at the expense of more torque**. These has to be thoroughly considered by the engineer dimensioning the vehicle to get the optimal outcome.

3.1.7 Mechanics – Driving system design and modelling

In order to develop this component, a conceptual study of the system was carried out in order to understand the loads it has to support and how to optimise the design. As it is symmetrical, only half of it has been analysed.

Basically, this part transmits the load and weight of the own robot to the wheel and the torque created by the motor and by the fail-safe brake. It is also required to be modular, so that any motor or any brake that complies with the adequate specifications can be installed. After all the analysis and a few iterations, the following solution is concluded (Figure 3.15).

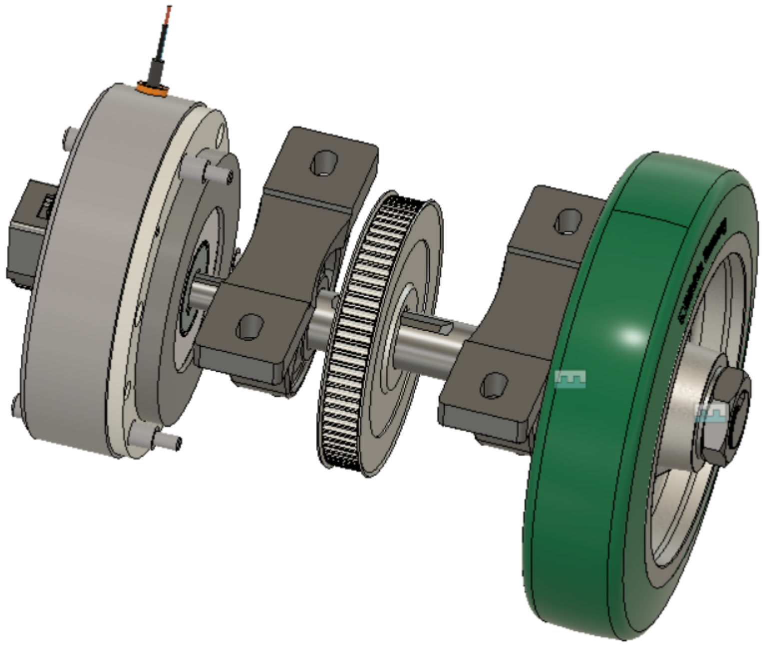

Figure 3.15 Shaft Assembly. From left to right: brake, bearing, pulley, bearing, wheel.

The main part of the assembly is the axle. It is attached to the chassis with two pillow block bearings, whose support is spherical and allows some misalignment (*Permissive misalignment* n.d.), so the shaft does not transmit moment to the bearings (only radial force), which would be harmful to them. For simulating purposes, the carbon steel C45 has been selected, as it is a common and relatively cheap material used for shafts and other machinery parts *(Shaft Material Selection,* 2019). The simulation shows the stresses that the shaft suffers under an overload of 5000N (about 500Kg), and it gives a minimum safety factor of 3.5 (Figure 3.16). This ensures that it will not break in any real case, since the maximum static load on each shaft will be around 175Kg (half of 70% of the maximum total weigh estimated at 500Kg).

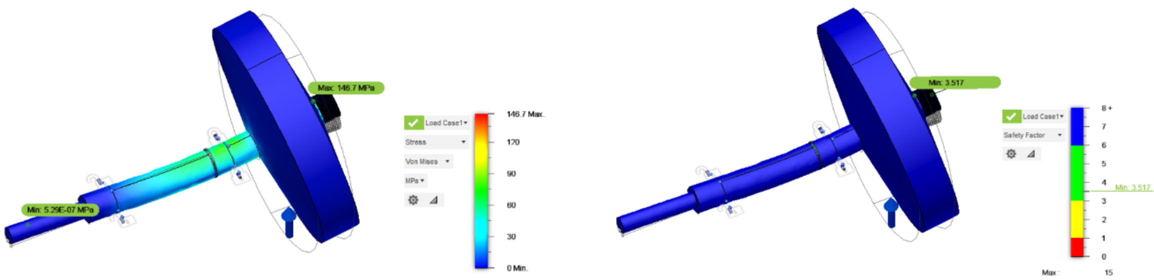

Figure 3.16 Shaft simulation: stress (left) and safety factor (right)

To model the wheel, an industrial real example (*Product GSTN 200/25H7* n.d.) has been included, which lives up to the loading requirements. It is composed of a cast iron hub and a polyurethane tyre, and it is assembled on the shaft as close as possible to the main bearing (which carries most of the weight), so that as little bending moment as possible is transmitted to the shaft. In the first iterations this was not the case, as it was considered to mount the pulley between the chassis and the wheel, but the simulation showed that the axle was subjected to much more stress.

There are two cases which should be compatible regarding the motor attachment to the frame: vertical or horizontal flange. The bracket is designed from steel sheet metal (although it could also be made from aluminium) and is bolted to the main chassis (Figure 3.17). This allows to change the brake or the motor for a different one if needed, by just replicating the sheet metal bracket with the new bolting pattern. This support is adjustable to allow tightening of the belt. Due to the high torque requirements, it is necessary for the motor to incorporate a reduction gearbox at the output shaft, which combined with the ratio of the pulleys must satisfy the required torque and speed calculated previously. Simplified models of generic motors have been created, which are usually commercialised for small electric vehicles such as bicycles, so they are widely available on the market. These are brushed DC motors rated at around 500w, usually running at 24V, although there are plenty of versions between 12V and 60V. There are also brushless DC versions, which tend to be more efficient and powerful, even though the choice of using one or the other will depend on the controller available. The integrated gear ratios are around 6.5:1, which combined with the 16 tooth pulley on the motor and 72 on the shaft, gives a final drive ratio of 29.25:1.

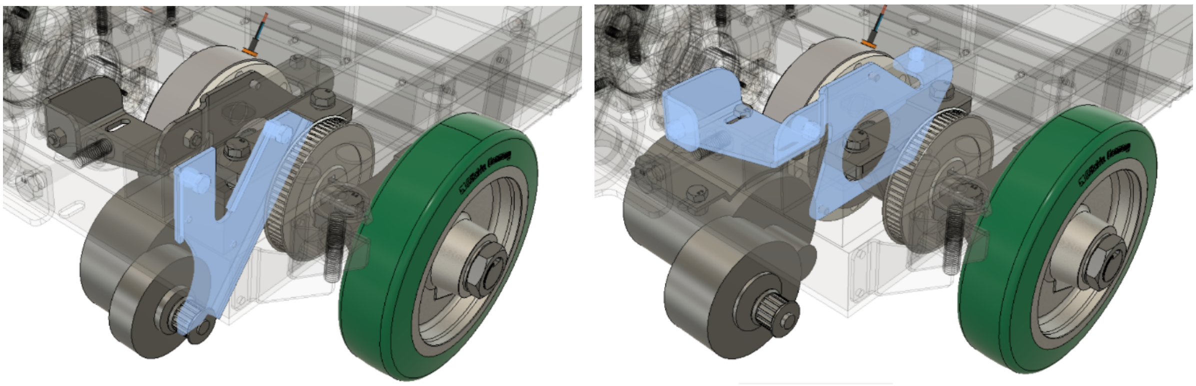

Figure 3.17 Motors and brake brackets, vertical (left) and horizontal (right) flanges.

Most of the available industrial brakes that satisfy this application are very similar in design, sharing among other things the type of attachment to the chassis, using a plate perpendicular to the axle. It is combined with the horizontal motor bracket (Figure 3.17), as they are formed from the same sheet metal. It is important to note that the position of the brake has been decided to be directly on the shaft itself for safety reasons. The idea of integrating it into the motor was considered to make it more compact, but in this case all the safety would depend on the belt, a relatively weak component. Any brake that fits in the dedicated space and is capable of applying sufficient torque can be used, just by changing the bolt pattern and possibly adjusting the shaft tip diameter or key size.

Last but not least, an encoder is necessary to provide feedback of the rotation of the wheel (and consequently how the vehicle is moving relative to the floor). It is supported by a plastic part to the bottom end of the brake. This part can be 3D-printed to accommodate any type of encoder (Figure 3.18). The encoder is built in the end shaft instead of the motor shaft to avoid backlash and gain accuracy.

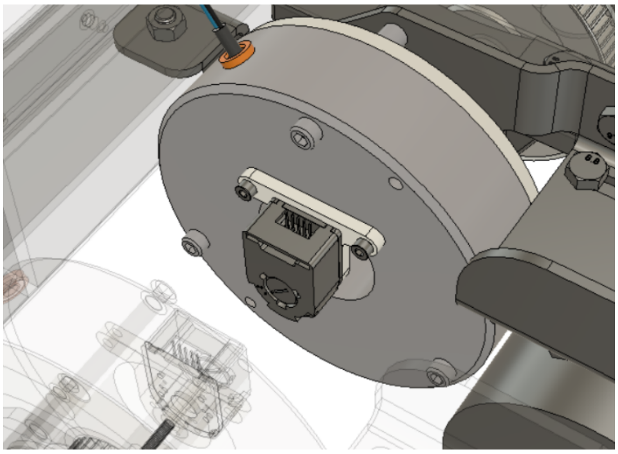

Figure 3.18 Encoder

3.1.8 Frame – design and modelling

The main elements of the vehicle (drive system, battery and casters) have been taken as the starting point to design the chassis, a simple but effective and robust structure has been approached, which joins these elements and distributes the load to the wheels. The arrangement of the different elements, most of which are bolted on, has been chosen to distribute most of the weight to the drive wheels. The frame is made of structural steel tube, specifically SHS (Square Hollow Section) of size 50x50x2.5mm and 40x40x2mm (Figure 3.19). The battery compartment is also built into the chassis, made from steel sheet metal.

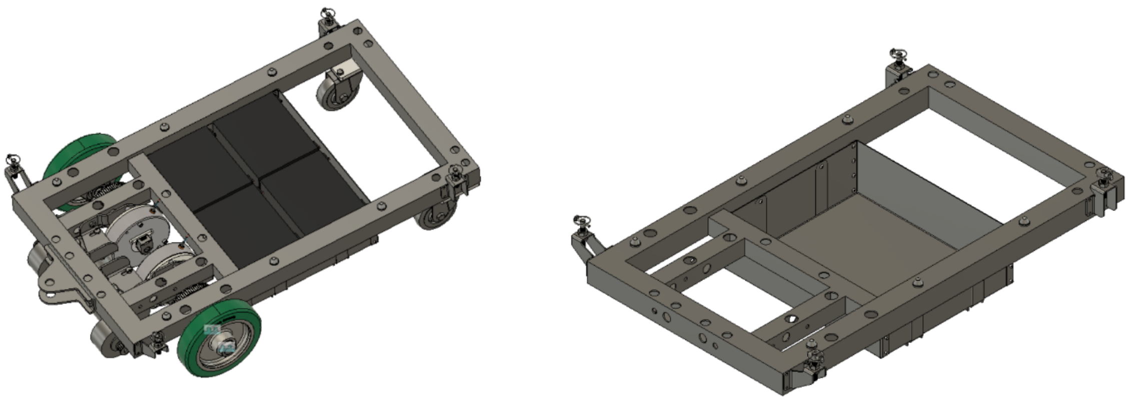

Figure 3.19 Main frame of the vehicle, with (left) and without (right) the main elements.

To ensure that the chassis can withstand the loads without problems, several simulations have been carried out. Two scenarios have been set up, both with an overload of 5000N (about 500Kg). In the first scenario the load is evenly distributed on the chassis supports, on which the load platform is mounted (see in the next section), and in the second case a poorly distributed load is assumed, which transfer all the weight to a single point. The latter would be the worst case, as all the force is concentrated and compromises the structure more.

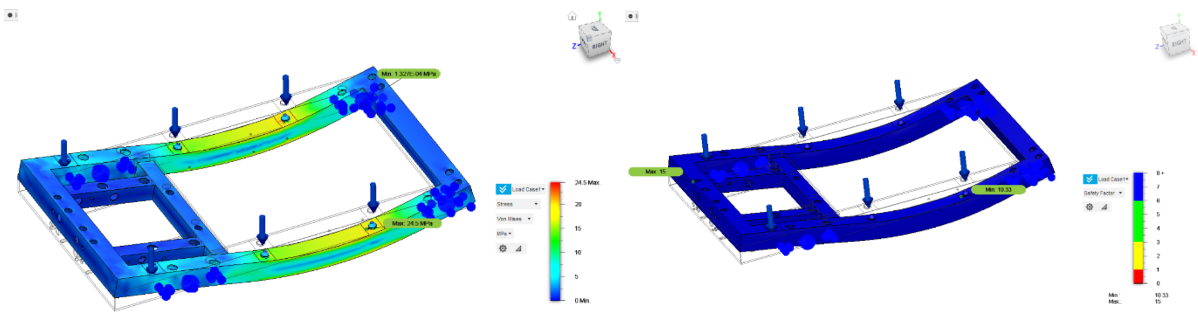

Figure 3.20 Frame stresses (left) and safety factor (right) under an evenly distributed load.

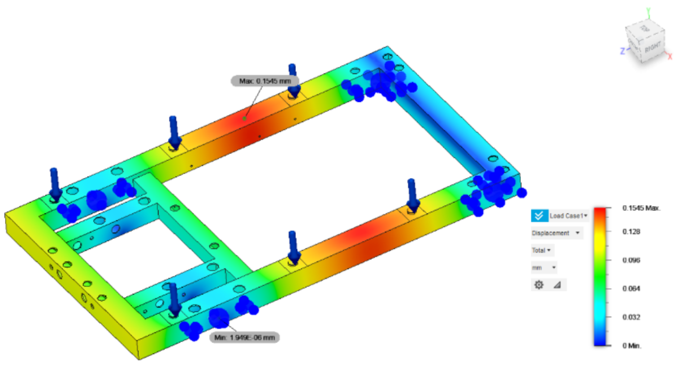

Figure 3.21 Real deformation under an evenly distributed load.

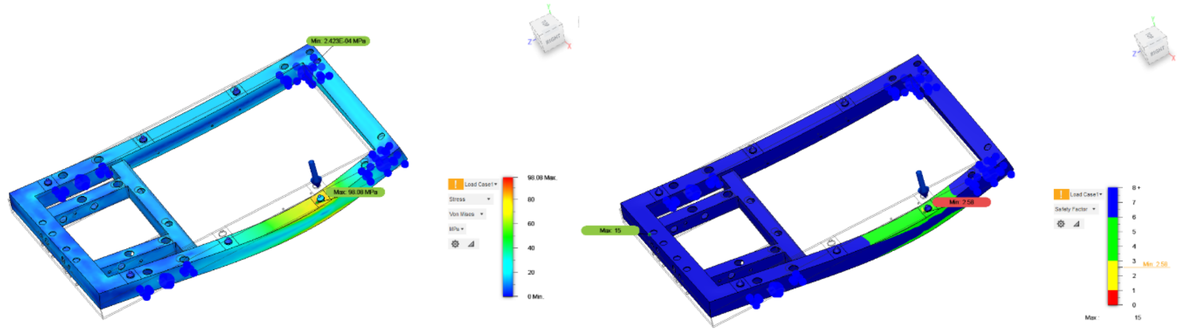

Figure 3.22 Stresses and safety factor under a concentrated load.

The simulation shows that the frame will hold perfectly under the most typical distributed load, with a safety factor of 10.3 (Figure 3.20), and insignificant deformations of negligible deformations of 0.15mm at most (Figure 3.21). Under the worst-case scenario, the frame withstands the load as well, although more compromised, reaching a safety factor of 2.58 (Figure 3.22). Nevertheless, this is a rare extreme case, with an overload and moreover resting on a single point. All in all, the test indicates that the frame would effortlessly handle the typical tough industry environments.

3.1.9 Bodywork and load platform

The main concern has been to create a loading platform combined with the bodywork, interchangeable so as to suit each specific use. It is therefore possible to use a flat load platform (Figure 3.23), to install a fixture for a specific part, or to install a body without a platform if it is going to be used only as a tugger. For this flexibility purpose, a fast-coupling system has been implemented, secured with pins

(Figure 3.24). The weight held by the subframe is directly applied to the chassis, while the pins prevent the platform from being accidentally lifted.

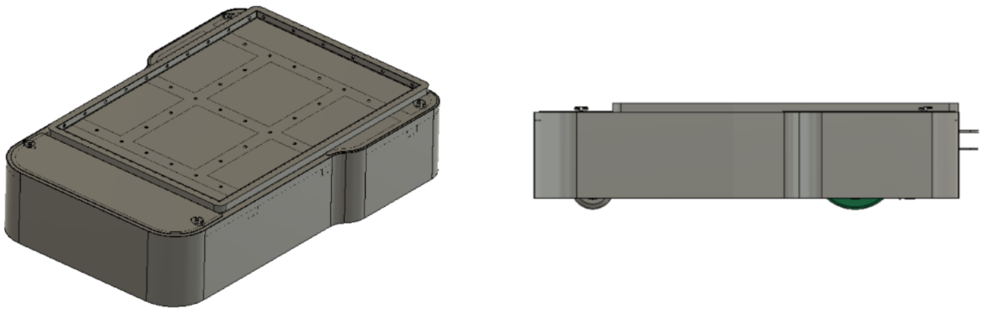

Figure 3.23 Bodyshell from top left and side persepective

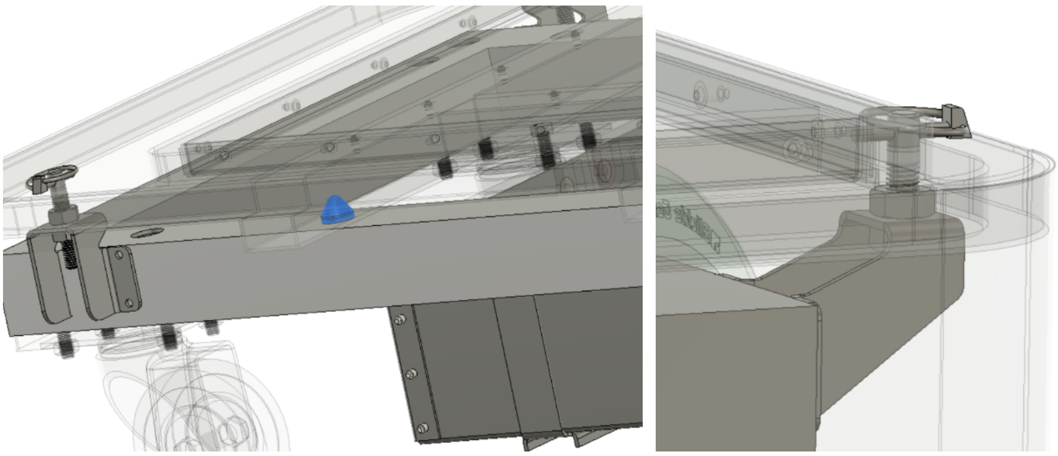

Figure 3.24 Fast-coupling system for the bodywork. The highlighted pin is one of the 6 that hold the subframe aligned to the main frame to transmit the loads, while the quick-release pins (right) secure the structure vertically.

The load platform has been developed to be simple and robust, same principles applied to the main chassis. It comprehends a substructure of SHS steel tube of size 40x40x2mm that spreads over the main frame the load evened by the steel sheet. The simulation has been carried with an overload of 10KN (about 1000Kg) evenly distributed over the platform (Figure 3.25), in order to verify a case with a normal load of less than 500Kg which is not evenly distribute. This fact evidences the capabilities of the structure against the industrial environments.

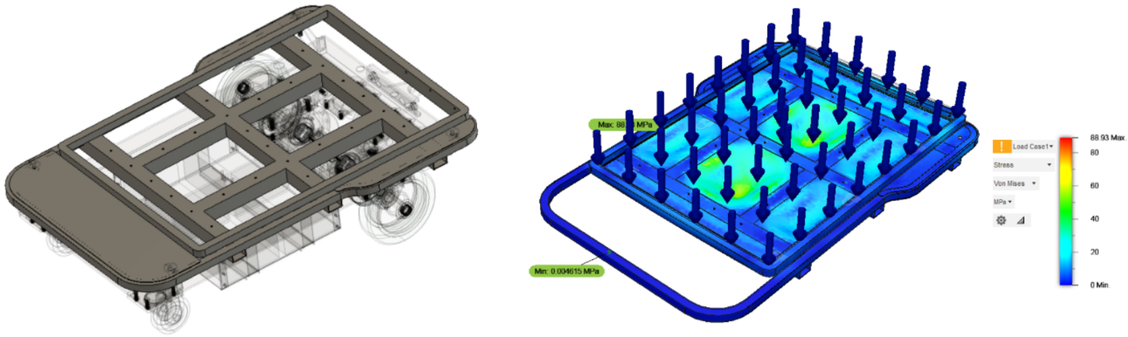

Figure 3.25 Load platform sub-structure and simulation.

3.1.10 Electronics

In accordance with EN ISO 3691-4:2020, the electronic equipment must agree with EN 1175:2020. This standard separately covers general electronic, energy source, drive system, electric load handling system, steering and software requirements of industrial trucks (SS-EN 1175:2020). It also conducts a verification process. On the whole, software (typology), batteries and circuits must check some typical industrial safety measures (electrical isolation, overvoltages, connectors, water and dust…) whereas the other systems have to meet some performance levels. Further information is annexed at A4 and A5.

3.1.11 Navigation and Safety Sensors

First of all, it is worth mentioning that there should be a distinction for navigation-destined and safety-destined sensors. Vehicle guidance could be accomplished via software (hard-coded routes, named free navigation (Ullrich 2015)) if the trajectories were described from first instance, yet the use of sensors for navigation is ubiquitous (Feledy and Luttenberger 2017). Other novel technique is using the received strength of signal (RSS) of an external sensor to locate the robot (Deshpande et at. 2016). In contrast LiDAR consists of presence sensors exclusively.

According to Wang (2020), AGVs can detect their surroundings by means of diverse technologies, involving camera, SONAR, RADAR, barcode navigation and LiDAR. Pereira (2021) builds on top of that and adds line detection and reflectors to the stack. While SONAR, RADAR, barcode and line detection are reasonably cost-effective, simple to implement and well-functioning but lacking sensitivity most of the times; camera and LiDAR bring elevated flexibility and resolution (Wang 2020). What is more, as cameras are not fit for dimly lit environments and can be affected by shadows, LiDAR is the norm and most effective solution, especially within the industrial realm, as they can comply as both a safety and navigation sensor.

Modern industrial AGVs may contain several LiDAR sensors in different orientations and positions, so that a single sensor on top of the vehicle could detect its surroundings and carry the navigation duty, whereas a couple sensors on ground level would make sure no one is within the vehicle's reach, acting as safety measures (Bosio 2018). On the other side, cameras and LiDAR may require embedded image processing, and hence a graphical unit, which adds the installation procedure, software complexity and price to an already economically disadvantageous option. The simpler gauges could thereby prove themselves useful for simple or isolated guidance applications. However, the factor ultimately tipping the balance toward the use of one sensor or another is the AGV being industrially prepared, i.e. it complies to EN ISO 3691-4:2020. To fulfil this the safety sensors must be rapid-response, high-resolution; so that in practice LiDAR is almost a constant requirement (Bosio 2018). In a less demanding case, any other object detection sensor could correctly detect incoming obstacles or people (Figure 3.26).

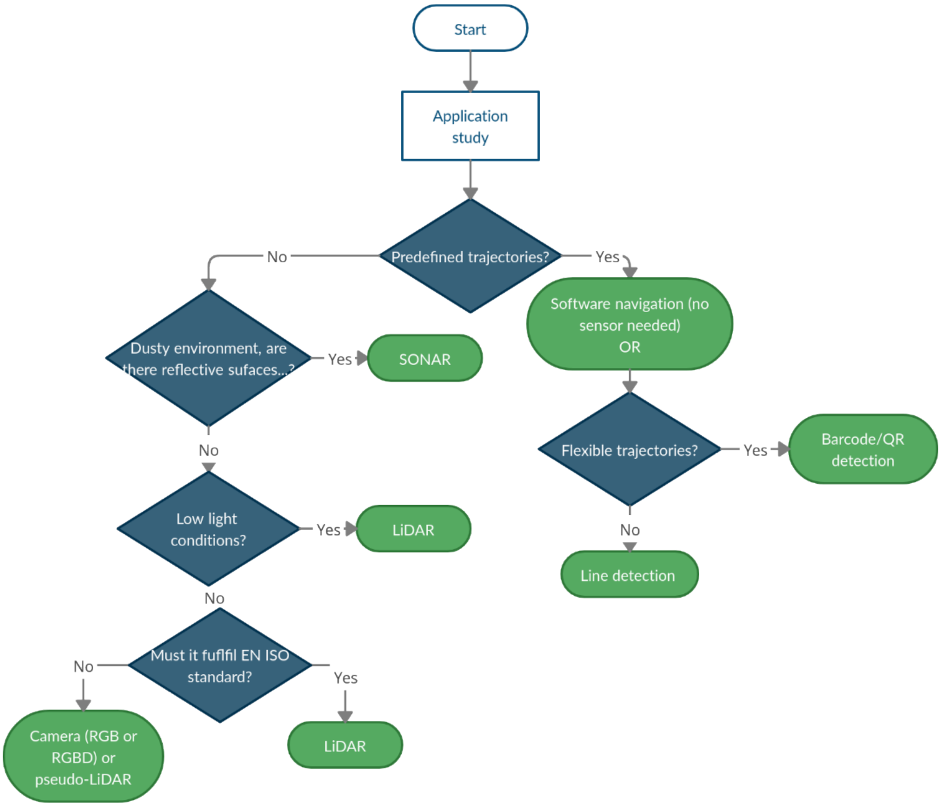

Figure 3.26 Decision flowchart for navigation sensor type, prioritizing economic preferences.

Despite Figure 3.26, it is worth mentioning that RGBD (*Red-Green-Blue-Depth)* cameras are more and more present amongst industrial AGVs and AMRs (Debeunne 2020), so most surely they will compete with LiDAR as the reference sensor for odometry. Nowadays, though, LiDAR is the safer and more reputable device. RGBD cameras fall behind in outdoor environments too. Interestingly, both technologies gain an edge when they are complemented by an Inertial Measurement Unit, or IMU, which could make them more competitive in most situations (Debeunne 2020).

All in all (Figure 3.27), **LiDAR sensors** are the most recurring ones amidst industrial usage because of its quickness, precision and easiness of use (Debeunne 2020). The two techniques a LiDAR fit for robotics may contain are solid-state, meaning there is a wide array of immobile sensors, and by means of lens some angle of vision is achieved; or rotating, i.e., there is a thinner array of sensors that rotates to cover up its surroundings. Generally, rotating are a more expensive option but with a higher angle of sight (normally the full 360°), whereas solid-state are more durable as they lack moving parts (Petit 2020).

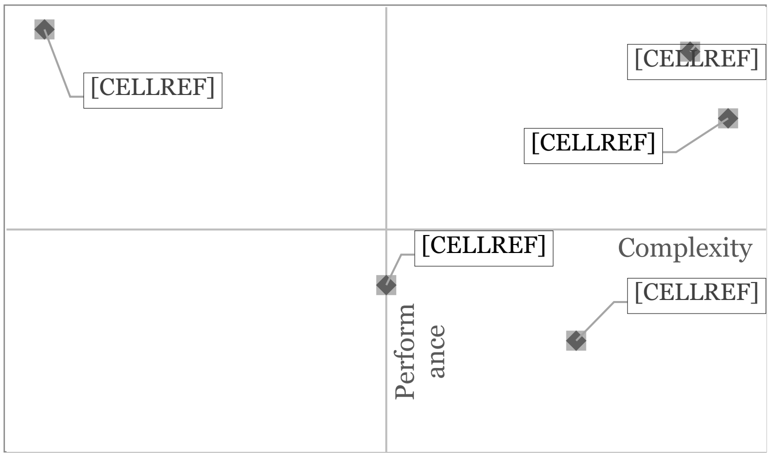

Figure 3.27 Sensors plotted according to their complexity and performance. (top right corner represents highest complexity and performance)

3.1.12 Processing units

The processing behind an AGV can be split in the systems outside and inside it. As Feledy and Luttenberger (2017) puts it, the guidance control system is responsible for intercommunicating all of the AGVs reciprocally and the peripheral equipment that may be used. This system is ruled by the internal logistics system and it commands the vehicle guidance control of each AGV (Figure 3.28).

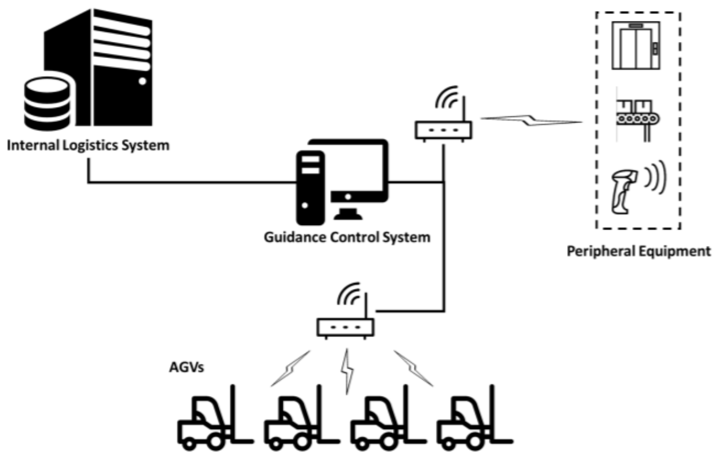

Figure 3.28 Control hierarchy. Each AGV has a vehicle guidance control. Source: Feledy and Luttenberger (2017)

As far as Ullrich (2015) is concerned, the vehicle guidance control is composed of the hardware and software in charge of the processes inside the AGV, in other words, it is the main processing unit in the vehicle. Ullrich states that this unit could be either a single-board computer (SBC), a storage-programmable guidance system, an individually designed computer based on microcontrollers or a multi-board computer; being the first two the most common alternatives the ones evaluated.

On an industrial scale, all of these options can be considered depending on the complexity and computational power the vehicle requires (Table 3.6). If the goal is pedagogic or of development, a less prepared computer or controller can be used, such as a Raspberry Pi (Amsters & Staels 2020, Dares 2020).

Table 3.6 Diverse vehicle guidance control options. It is worth mentioning that an AMR can be perfectly powered by non-industrial SBC as a Raspberry Pi board or similar, but they are not as powerful as the industrial SBCs. Sources: Dares et al. (2020), https://buy.advantech.eu/, https://www.industrialshields.com/shop

Type	Computational power	Industrial	Price	Usage
Industrial SBC	High/very high	Yes	Very high (>1000$)	AMR/Advanced AGV
PLC	Medium/low	Yes	High (>200$)	AGV
Non-industrial SBC or µC	Medium/low in most cases	No	Low (<200$)	Education and development

Even if an industrial scope were looked for, one can find OSH-based PLCs and SBCs, mainly based on Arduino[8] or ESP32 and (although not OS) featuring Raspberry Pi[9] boards, respectively.

If the AGV worked with computer vision (visual SLAM or vSLAM), a GPU is a must-have. One of the most widely and effectively used for AI algorithms is the NVIDIA Jetson series along with the ISAAC platform (Abel 2020), which has several models suited for differently demanding applications. Although they are not OS, their versatility has given them a spot even in low-budget projects (Dzezhyts 2020).

3.1.13 Communications

Having a robust Wireless Local Area Network (WLAN) interconnecting the AGVS is indispensable (Feledy and Luttenberger 2017, Ullrich 2015). Communications represent the link between the guidance control system and the vehicle guidance control, hence there must be a stable, constant connection between them in almost any type of AGV. There is not a clear consensus on communication systems for AGVs, therefore plenty of different solutions arise when establishing an Industrial WLAN (Wilamowski and Irwin 2011, Kongezos et al. 2002), so the choice would most of the times depend on the manufacturer's personal criteria.

The burst of new technologies, being 5G the most notable, has permitted a massive development of coordination among factory facilities (known as Industrial Internet of Things or IIoT) and mobile robots in particular (Oyekanlu et al. 2020). Lately, diverse technologies such as UWB, Wi-Fi or RFID have been implemented to simultaneously transmit data and help locate the vehicle, still it is predicted that 5G will became the norm (Oyekanlu et al. 2020).

3.1.14 Software

Low-level software

This software is basically all the rudimental programs to make all the hardware function interconnectedly, that is to say, the drivers of each component. They are exclusive to the hardware.

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[8] https://www.controllino.com

[9] https://www.industrialshields.com/shop/category/controllers-cpu-ios-com-plc-10-i-os-controller-family-10-i-os-controller-cpu-63

High-level software: keeping the trajectory

When having a pre-loaded map, a particle filter is one relatively simple outcome to locate the vehicle within the warehouse. They are frequently based on Monte Carlo methods and are widely investigated (Oxenstierna 2019; Senington, Schmidt and Syberfeldt 2021), although there is not an axiomatic tool to use. If there is not such initial input, as it usually occurs, the most recurrent approach is Simultaneous Location and Mapping (SLAM). It can be found unrestrictedly on the internet, as a node of ROS or a *github* repository.

High-level software: fleet management and path planning

Trajectory creation is a fairly simple programming task. The known locations in the map form a graph and by means of algorithms such as Floyd-Warshall's, Djikstra's (1959) (Solichudin 2020) or A-star (Wang 2015) the path is generated.

If an amateur, research or just modular purpose is sought, the Robot Operating System (ROS) represents a versatile and open-source solution. Although it was not formerly an industrial software, and as a matter of fact there is a ROS-Industrial for manipulators – it has steadily carved out a place for itself among AGVs and AMRs (Dalgaard 2021).-a simple-minded program for low-complexity cases called OpenTCS, but the most normalized industrial software are commercial ones such as Oceaneering's[10] (*Automated Guided Vehicle (AGV) Fleet Management Platform Market - Global Industry Analysis, Size, Share, Growth, Trends and Forecast 2018 - 2026* n.d.).

3.1.15 Certification of EN ISO 3691:4-2020

For the AGV to be suited for a factory, it has been designed trying to fulfil the requirements the EN ISO 3691-4:2020 sets. These have to be verified, however. This is a task for an accreditation body (also known as certification body), here is the turning point that separates truly industrial vehicles from normal AGVs. Certifying a vehicle is an expensive and thorough procedure. There could be resulting disagreements between an OS vehicle, which is thought to be modified and changed, and the sealed industrial standard. This may lead to a loss in the value of OSH in industry. Another issue might come along with modifications, as if a vehicle is changed taking advantage of its modularity, the standard may have to be certified again.

The standard *per se* consists of a set of matchings between features of the vehicle and performance levels, in a way that everything has to perform at least as well as their respective level. The detailed information is referred in the appendices A5 and A7.

[10] https://www.oceaneering.com/automated-guided-vehicles/agv-control-software/

4. Results

The results will be shown in the shape of different reproducible configurations that could find a spot in current production systems and development environments. They will be divided in sizes (clothes sizes S, M and L for simplicity's sake) and within each a bunch of models are going to be under judgement. They are no more that possible outcomes for some goals, and anyone could just create one of their own. It should be noted that there has to be a distinction between a tugger, an underride and a hybrid AGV as, even in a slight fashion, involve differences among each other. Indeed, a tugger is a bit more complex than an underride, as they require extra parts to link the carriages and conform a much longer convoy, henceforth becoming a tougher programming and safety challenge.

4.1 Small Configurations (S size)

These represent the smaller type of AGV and the most affordable. Its main purpose is the transportation of expendable loads in the simplest manner. Therefore, the choice of components is done in the humblest way possible to flatten the costs. They may result truly handy for education and testing as simple, reliable but still tweakable vehicles. The chassis they would employ is smaller than the one created, they ought to transport loads around a hundred kilograms. Although the general structure and disposition is equivalent, it must be resized depending on the battery, the mechanical viscera shrunk to satisfy the physical demands and the wheels adapted to meet the load impositions; providing an economic version is in the scope. An industrial (S') and a "miscellaneous-purpose" (S) version should be hence designed (Table 4.1).

Table 4.1 S size AGV configurations, in red non-OSH components, title in blue if the model is industrial.

	S	S'
Battery	NMC (specially if it is an underride)	
Traction solution	Belt and pulley	
Wheel diameter	~15 cm	
Mechanic solution	Double-flange, no brake	Hub wheel drive with brake incorporated
Motor	OpenTorque Actuator	
Controller	ODrive	Brushless, acc. motor specs
Processing unit	µC (Arduino)	PLC (Controllino or a shielded Arduino)
Sensor	Ultrasound	LiDAR (safety) and QR-detection (navigation)
Software, location	ROS, RSS location	OpenTCS

4.2 Medium Configurations (M size)

These are essentially vehicles that can handle a load around half a tonne (a tugger or hybrid could stand this while an underride would not hold more than 400 kg) and resemble the industrial vehicles of the kind. Three different versions have been kept in mind, starting with a "classical" AGV (M') and augmenting complexity at the expense of performance, approaching the AMR concept. The chassis and mechanisms could perfectly be the ones studied without the need of any adaptation (Table 4.2).

Table 4.2 M size AGV configurations, in red non-OSH components, title in blue if the model is industrial.

	M	M'	M''
Battery	Lead-acid	LFP	Lead-acid
Traction solution	Belt and pulley		
Mechanic solution	Two mobile shafts		Double flange hub
Wheel diameter	20 cm		
Motor	Brushed/Brushless acc. controller (Power > 450 W)	Integrated driving system (controller usually integrated)	Brushed/Brushless acc. controller
Controller	Generic H-bridge controller/ ODrive		ODrive
Processing unit	SBC	PLC	SBC +NVidia Jetson
Sensor	LiDAR	LiDAR	RGBD
Software	¿Industrial ROS, filter?	Oceaneering	ROS

All the vehicles reviewed thus far might be summarized in a chart to easily picture all the different versions in the performance-complexity realm, so that the choice of the manufacturer becomes less exhaustive and more contextualized (Figure 4.1).

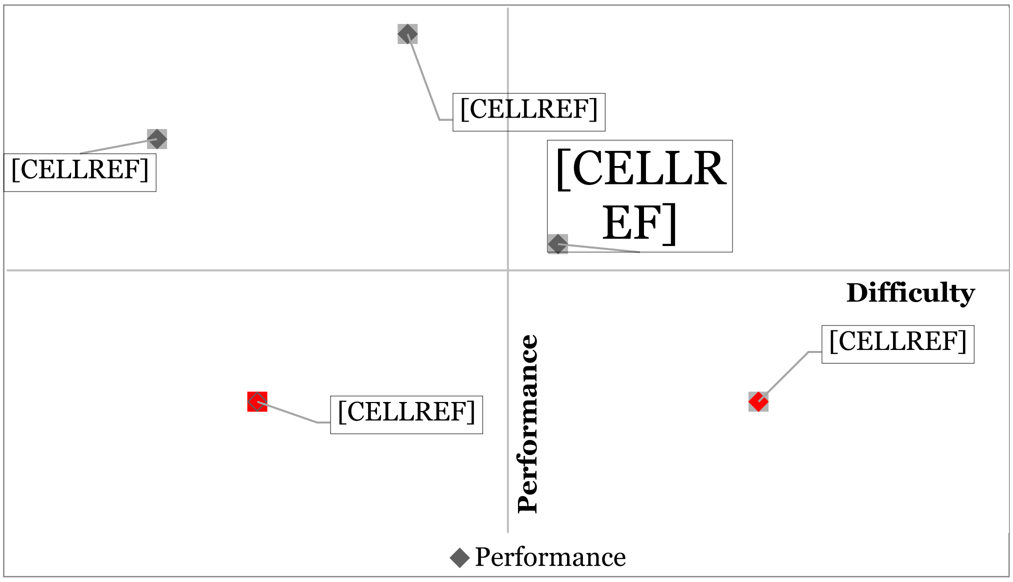

Figure 4.1 Summary of the different configurations as a relation between difficulty of implementation and performance. The term "difficulty" has replaced "complexity" as the latter can be mistaken with software complexity.

4.3 Large Configurations (L size)

Coming up with a model that handles a load around 1000 kilograms would imply making a more robust frame, because of that no configurations for this size have been selected. Still, this is a feasible task that would just involve using thicker profiles and stronger mechanical pieces. Likewise, the modular features would be normally attainable. For the rest of components, the criteria are similar.

4.4 Economic analysis

It can be derived from the component and certification research that, although OS, an industrial vehicle will always be expensive compared to one that has other purposes. Thus, there exists a financial threshold separating both cases (Figure 4.2). Determining a sensible budget is a task exceeding the capabilities of this project, there is plethora of details to consider that could cause significant turbulences in the device final price. Manufacturing, production volume, certification or quality of components are some of these factors that need deep research previous to any price proposal.

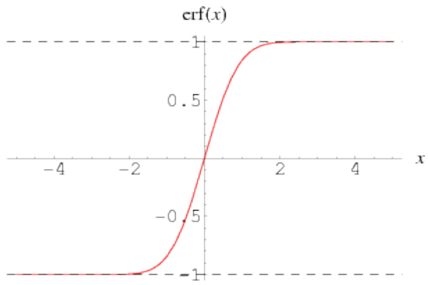

Figure 4.2 The relation between industry-fit and price can be understood as an error-function-shaped curve, where the vertical axis represents price and the horizontal axis the number of industrial components. There is a point of exponential growth which could represent the certification of the vehicle. Source: *https://mathworld.wolfram.com/Erf.html*

5. Discussion

As it has been shown, although it is possible to manufacture an OSH AGV or AMR, there are plenty of limitations to this accomplishment. These limitations exponentially add up when the vehicle is industrial. Taking into account all the benefits OSH brings, the fact that there are heavy impediments that have precluded OSH AGVs in the current market is conceivable. On the other hand, there exists a chance that simply no one has been willing to invest the time and money to deliver such a project. One way or another, one should bear in mind that creating an OS, configurable product implies quite steep first years.

5.1 Methodology and results evaluation

The methodology differs between the literature review and the vehicle design itself. Since most of the component choice came across with profound research about the component's nature and implementations, the relevance of information obtention methods peaks. As it has been mentioned, the literature review has not been systematic (due to the elevated variability of the project contents), from which the most impartial contents have been tried to select and compare. Despite it seems conceptually manageable, difficulties have sprouted when striving to find objective, straightforward research. Particularly in the AGV hardware design – there was no consensus on how to do the mechanics and structures – and battery chemistry choice – not only does it lack unanimity, but papers also show unmatching results for similar experiments – areas, which apart from significantly slowing down investigation tasks compromise the validity of the results.

Pertain to the results themselves, the display of such is maybe not the optimal (certainly the optimal will be a *github* repository), but they encapsulate a more practical perspective, rather than one focused on the component choice that has formed the greatest part of the project, as these represent more of the nuts and bolts of the project instead of the final result intended. These results may find usefulness as a "AGV building 101" guide, and the component analysis as a deeper, more technical part. All in all, the component choice is aimed at hardware enthusiasts and the results at software or AGV in general ones. In this case, the parts do not make up the whole, then having well-delimited components may not guarantee that the whole vehicle functions correctly. Software implementation, fine tuning between among hardware and software and testing is fundamental, leaving consequently a not immediate solvable "to-do" list to cope prior to project entire completion.

5.2 Aim and research question evaluation

In order to evaluate the aim, which is to "explore the practicability", the term **practicability** shall be judged and restricted within limits: what makes something practicable? If it is just the mere fact that it can be created, the aim would have been clearly evidenced. Nevertheless, what is essentially looked for is the solution being a possible real solution for a real problem, with real economic and flexibility prospects that could boil down to the subsequent question: **"To which extent is exactly an OSH AGV or AMR practicable?"** This is a much harder problem to tackle, and that will be just partially solved in this thesis, known the size of it.

An OSH autonomous vehicle is absolutely feasible with educational purposes (Amsters and Staels 2019), from there making it officially modular is just a small step forward. The true issue comes with industry-related applications. They could be divided into development and labour functions. The first one could become a niche for this product and contribute to AGV and AMR progress, even though this a market that does not exist to the day. As for labour, open source components are tough to develop and generally not certified, so they would have to undergo intense testing to prove a trustworthy functionality, becoming an economic downside. Henceforth, the odds of seeing OS vehicles in the industry are not favourable in the short term, the paradigm shift may take more time and research. It is not an impossible reality in a later future, however.

Another doubt worth retrieving is: **where can OSH contribute to AGV and AMR systems?** If an industrial vehicle could not be entirely OS, perhaps there are some areas in which having OS technologies brings plenty of advantages. An open frame and mechanical disposition enable easy fixings, component substitutions and new vehicle versions. OSS could also deliver more efficient and updated programs (Ghapanchi et. al 2014). In contrast, OS finds its hindrances in its own size (it is so large that it lacks clear aim and loads of projects are constantly being discarded) and the lack of economical revenue (Raymond 2000).

If a manufacturer had the intentions of constructing an open hardware AGV or AMR, a recommendation would suggest that instead of making it OSH, the focus leaned on the specific functionality of the vehicle, and then take as many OSH components as possible, if they fit the application. Otherwise, a lot of time will be lost researching on AGV-OSH that might not really exist. The manufacturer's aim should be clearly set then in the vehicle to design.

5.3 Technology, Society and the Environment

As it has been discussed in the introduction, the technological and social impact OS yields stands out. Not restricting one's work is morally rewarding as well. Regarding this piece of work, it could be expected that its modular philosophy, as well as it being an industrial device will cause some additional effect on technology. On the other side of the spectrum, it could still work as inspiration for future, larger size projects (Scacchi 2004). The mindset of doing everything as generalized as possible to allow configurable design has been present all along the project, so that the assumptions made in the sustainability aspects are not discarded. All of these aspects of course remain hypothetical notwithstanding.

This kind of frameworks cause in theory no harm to the economic status quo, as they do not interfere in anyway nor destroy any market spot, instead bring the possibility to broaden the AGV and AMR market and take down the walls that prevent less affluent companies from using autonomous vehicles. In this sense, a current necessity is not satisfied but the upcoming one of affordable AGVs.

The OSH AGV represents a valuable environmental asset in logistics: not only does it work efficiently – electricity-powered, can be designed not to carry a smaller load than its capacity –, but also allows the use of recycled components and analogously recycling redundant parts. Although it may not turn out as ideal, utilizing OS normally represents a pretty efficient solution (*Open Source Study* 2021).

6. Conclusions

Building an OSH automated guided vehicle from scratch is not an easy task by any means. A massive span of factors and details must be taken in consideration to ensure a robust functionality, which may be where the strength of OS lies: the framework could be now embraced and developed to further stages, with new perspectives and initiatives, but the final outcome is uncertain. Indeed, this has only been the initial footstep on an unbeaten track, which may split in different paths and may or may not be walked across. Still, this project to some extent succeeds to cover the first development stages of an open hardware AGV or AMR and contemplates the benefits and drawbacks of constructing one.

In this day and age, where OSH is present but has not blossomed yet, an industrial device that fully operates on OS and competes with their commercial analogues would suppose a remarkable feat, owing to the fact there are still a few of intermediate phases in between, such as OSH traction solutions, vehicles, motors, etcetera. As a temporary solution, though, there are some uses these vehicles can provide, and probably with a few more expansion low-key industrial applications could be tackled.

As a personal critique, employing a standardized methodology and giving emphasis on advancing the small fundamental parts instead of on the whole vehicle has proved to be utterly advantageous and something to be adopted in the future. On the other hand, besides from the difficulties finding reliable, straightforward data, the overwhelming size of the project has blurred the organization capabilities, which have prevented the building and testing of a real model, something that is crucial. This is why a framework of this scale might better be handled by a department in the university, and its subsequent work distributed among students and final degree/master's project.

6.1 Future work

The number of unfinished or improvable tasks this project leaves is far from small. Despite the basics being established, these can be boundlessly enhanced, from a quality (research and experiments to support some of the argumentations, standardization of the components in a real case) and quantity point of view (the more the components and configurations the better). Besides, the usefulness of Oberloier and Pearce's (2018) methodology should also be evaluated to either verify or modify it, the model created is not 100 % ISO compatible and a real model, that could help deal with these problems, has not been constructed. A new aim will strive to **demonstrate the practicability** of OSH AGVs and/or AMRs. In short:

- Develop on hardware:
  - Generalize the connections between boards and peripherals.
  - Further research on every component and choice of real models (for instance, instead of just saying LFP battery, come up with a real LFP battery model, that can be easily acquired according to the methodology)
  - Simulations to test hardware
  - Study a load handling system.
  - Carts: conceptual and mechanical design (e.g. how they steer)
- Develop on **software (open source if possible)**
  - Communication protocols

    - Switch between tugger and underride?
    - Deeper research on trajectories and for fleet management
    - Implement the software (simulations or real model)
- Building a real and **a test model**
    - Autonomy and efficiency of the vehicle
- Probe methodology
- The standard research has been shallower than planned
    - Light and sound signals
    - Emergency buttons
    - HMI and interface in general

The more urgent priorities are in bold: building a prototype is vital to test everything stated in the chassis and mechanics sections, and a platform to evaluate the modularity. On the other hand, software has been superficially studied, so a more thorough go-through will confer completeness to the AGV, at least on a low scale, besides from simulation and real testing.

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Appendices

A1. Work Breakdown and Time Plan

In this compulsory appendix, the initial work breakdown and time plan (Gantt chart) for the project should be compared with an updated version which shows how the project actually took place. Discuss and reflect upon the differences between the original and the updated versions.

This appendix is related to one of the goals of the program, specifically, that students should be able to respond to challenges that arise during a long project and manage the deadlines accordingly. By reflecting on critical changes in both the planning and the direction of the project, an understanding of this aspect of project management can be demonstrated. Identify in general terms, those occasions in which the project underwent a substantial change; for instance, explain how and why the goals were reformulated during the project and how the milestones were met when these changes were made.

The initial plan was devoting the first two months for gathering information and goal setting, namely a solid conceptual model of what necessity had to be satisfied and what kind of solution had to be implemented. The following month or two's work would involve doing the real design and choosing all of the hardware and software that could suit the configurations that would eventually be decided. These configurations would ideally be determined in this span of time. Finally, a real model implementation for testing (at least partially) the legitimacy of the solution would be built. All along the duration of the project the documentation of the thesis had to be written (Figure A1.1).

Activity \ Week	3	5	7	9	11	13	15	17	19	21
Start	▮									
1 Literature review and industrial necessities study	■	■	■							
2 Deciding and developing a conceptual model		■	■	■						
3 Design of real, feasible frame				■	■	■				
4 Hardware / peripheral decision					■	■				
5 Different Configuration Setup					■	■				
6 Implementation							■	■	■	
7 Cost estimation					■	■				

8 Documentation & report										
9 Preparation of presentation										

Figure A1.1. Former Gantt diagram.

As it could be predicted, the working load massively exceeded the handling capacity, as each component demanded much more research than that planned, and therefore all parts were stretched, precluding any chance of building a real model (Figure A2.2).

Activity \ Week	3	5	7	9	11	13	15	17	19	21
Start										
1 Literature review and industrial necessities study										
2 Deciding and developing a conceptual model										
3 Design of real, feasible frame										
4 Hardware / peripheral decision										
5 Different Configuration Setup										
6 Implementation										
7 Cost estimation										
8 Documentation & report										
9 Preparation of presentation										

Figure A1.2. Final Gantt diagram, in red the discarded parts, in blue the new ones that replaced them.

The project certainly outsized our expectations. Still, evidencing scientifically each part was prioritized to finishing all of them, which can be seen as a wiser approach, despite leaving a monstrous amount of work ahead.

A2. Battery choice

In order to find the most profitable battery the optimal depth of discharge (DoD) must be found for each chemistry. As a matter of fact, the degree to which the battery is emptied significantly affects the number of cycles it will last (Figure A2.1).

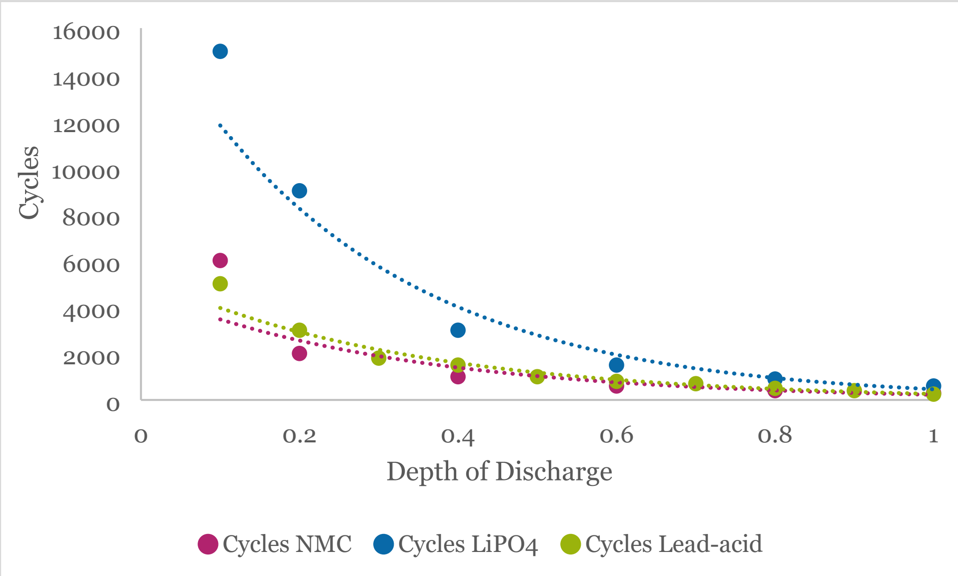


Figure A2.1. Cycle life of different types of batteries according to their depth of discharge (Battery University 2020, Norwatt 2018)

To obtain the best DoD, not the maximum number of cycles should be calculated, but the maximum amount of energy out of the battery. In other words, if low DoD is used, say 5%, many more cycles may be performed before the battery becomes obsolete, but those cycles would only take 5% of the maximum capacity. On the other hand, if an elevated (e.g., 95 %) DoD is applied, more energy will be extracted from each discharge but a smaller number of cycles as a trade-off.

Another important factor is that, once the cycles are depleted, the capacity is not down to 0 % but to 80 % as a rule, so that the battery can still be used with a DoD smaller than the 80 % of the former battery capacity. Thereby, a function that relates capacity and cycles elapsed is going to be necessary. The energy that the battery uses can be understood as the area of the function of capacity vs. cycles. For example, if the battery was always charged to its top and then completely discharged (DoD = 1), the area taken will be the whole enclosed between the curve and the two axes. However, if the DoD was smaller, a parallel curve starting at *1-DoD* will set the lower limit.

The number of cycles the battery withstands using a certain DoD is to be calculated (they may be named real cycles or C_r) to get the number of discharges that can be done before the capacity falls below the DoD that the application requires and the battery is discarded.

The simplest way to model the function relating capacity (k) to cycles (C) is a parabola (ref)[11], that passes through two key points: 0 cycles, 100% of capacity and tabled cycles (C_T), 80 % of capacity. Hence, if the capacity is expressed as a decimal instead of a percentage:

$$k\,(C) = 1 - m \cdot C^2 \qquad [1]$$

[11] The curve certainly could look like a logarithmic or exponential one, but an exponential model is much simpler and, although can carry some error (in the end it can be understood as a Taylor series), the approximation is within the error of the multiple batteries available.

This is the equation of a concave parabola that goes through the point (0, 1) as desired. The constant *m* is going to be calculated by forcing the point (C_T, 0,8). Evaluating in [1] and solving out:

$$0{,}8 = 1 - m \cdot C_T^2 \qquad [2]$$

$$m = \frac{0{,}2}{C_T^2} \qquad [3]$$

$$k\,(C) = 1 - \frac{0{,}2}{C_T^2} \cdot C^2 \qquad [4]$$

The tabled cycles, if modelled as an exponential function (with the help of the software Microsoft Excel 365), can be extracted for the DoD for each one of the three types of battery chemistry, as it follows:

$$C_T(DoD) = a \cdot e^{-b \cdot DoD} \qquad [5]$$

Where both *a* and b are positive terms. Thus, the capacity of battery would depend on both the cycles it has undergone and the DoD of these cycles. Replacing terms:

$$k\,(C, DoD) = 1 - \frac{0{,}2}{a \cdot e^{-2 \cdot b \cdot DoD}} \cdot C^2 \qquad [6]$$

Next up getting a function of the relative energy that is yielded from the battery (E_R) ought to be extracted. This unit can be understood as the number of discharges done times the percentage of the battery used per discharge. The number of discharges is the real cycles or C_R, and the battery percentage employed is the DoD. Subsequently:

$$E_R(DoD) = C_R\,(DoD) \cdot DoD \qquad [7]$$

This function [7] will ultimately be optimized to find a maximum and will grant the best DoD possible. As three different $C_R(DoD)$ are being deduced for each battery type, there will be different desired DoDs for lead, lithium nickel manganese cobalt oxide and lithium iron phosphate (Table A2.1). To surmise the C_R expression, a logical deduction must be fathomed: the C_R will be reached when the capacity is exactly the DoD, as afterwards the battery will last shorter than required. Evidently, the DoD is the percentage taken from the initial battery capacity, so that in this point where the capacity is the DoD the battery would need to be completely discharged to match the DoD of its initial self. Swapping terms in equation [6] the function for the real cycles is obtained:

$$DoD = 1 - \frac{0{,}2}{a \cdot e^{-2 \cdot b \cdot DoD}} \cdot \left(C_R(DoD)\right)^2 \qquad [8]$$

$$C_R\,(DoD) = \sqrt{\frac{(1 - DoD) \cdot (a \cdot e^{-2 \cdot b \cdot DoD})}{0{,}2}} = \sqrt{5 \cdot (1 - DoD) \cdot (a \cdot e^{-2 \cdot b \cdot DoD})} \qquad [9]$$

And the energy as a function of the DoD would be:

$$E_R(DoD) = DoD \cdot \sqrt{5 \cdot (1 - DoD) \cdot (a \cdot e^{-2 \cdot b \cdot DoD})} \qquad [10]$$

This will be the function whose maximum will tell the optimal DoD. By means of the first derivative – with respect to DoD as it is the unit that will optimize it –, the extrema will be obtained (DoD values that make it zero), and the second derivative will reveal the maxima and minima (when evaluating the mentioned DoD solutions). Henceforth,

$$\frac{\partial\, E_R(DoD)}{\partial\, DoD} = \sqrt{5\cdot\left(a\cdot e^{-2\cdot b\cdot DoD}\right)\cdot(1-DoD)} - \frac{a\cdot DoD\cdot\sqrt{5}\cdot e^{-2\cdot b\cdot DoD}\cdot(1+2\cdot b\cdot(1-}{2\cdot\sqrt{a\cdot(1-DoD)\cdot e^{-2\cdot b\cdot DoD}}} \quad [11]$$

The equation to solve and solutions if *b* is different from zero:

$$\frac{\partial\, E_R(DoD)}{\partial\, DoD} = 0 \quad [12]$$

$$DoD_1 = \frac{2\cdot b+3+\sqrt{4\cdot b^2-4\cdot b+9}}{4\cdot b} \quad [13]$$

$$DoD_2 = \frac{2\cdot b+3-\sqrt{4\cdot b^2-4\cdot b+9}}{4\cdot b} \quad [14]$$

Table A2.1 Coefficients of the exponential trend line of cycles vs. DoD equation.

$C_T(DoD) = a\cdot e^{-b\cdot DoD}$	a	b
Lead	5357,9	3,029
NMC	4697,4	3,041
LFP	16946	3,609

For simplicity's sake, prior to extracting the second derivative, the DoDs will be calculated according to the solutions obtained, and if some give a DoD that is negative or greater that one, it will be automatically discarded because of a lack of physical sense. Replacing *b* thus:

$$DoD_1Lead = 4{,}90 \quad [15]$$

$$DoD_1NMC = 4{,}21$$

$$DoD_1LFP = 4{,}01$$

These results are over 1, as the discharge cannot be larger than the capacity of the battery this solution is disposed. The second solution, though, shows different results:

$$DoD_2Lead = 0{,}269 \quad [16]$$

$$DoD_2NMC = 0{,}268$$

$$DoD_2LFP = 0{,}235$$

This could be considered a valid solution if the second derivative were less than zero (maximum, as the aim is getting the most energy possible). When calculating:

$$\frac{\partial^2\, E_R(DoD)}{\partial\, DoD^2} = \frac{a\cdot e^{-b\cdot DoD}\cdot(-4\cdot b\cdot(DoD-1)\cdot(DoD\cdot(b\cdot(DoD-1)-3)+2)-3\cdot Do}{4\cdot(DoD-1)\cdot\sqrt{a-a\cdot DoD}} \quad [17]$$

When substituting the deducted solution [16] in this last formula, for the three *b* and the three DoDs, the obtained result is roughly the following:

$$\frac{\partial^2 E_R(DoD_2)}{\partial DoD^2} \approx -4 \cdot \sqrt{a} < 0 \qquad [18]$$

As a is greater than 0 in our case, [18] will be always negative and this implies the solution found is a maximum.

With the optimal DoDs, the last step is obtaining the profitability for every type of battery. Each of them has a ratio of price per energy unit (P), nevertheless only a percentage of the energy (DoD) is used per discharge and thus the price increases. Besides, another factor to take into account is the real cycles used from each battery, as a result the new price ratio should be per battery cycle:

$$P' = \frac{P}{DoD \cdot C_R} = \frac{P}{DoD \cdot \sqrt{5 \cdot (1 - DoD) \cdot (a \cdot e^{-2 \cdot b \cdot DoD})}} \qquad [19]$$

As a result, if a generalized price-energy rate (Mongird et al. 2019) and deduced DoDs evaluated, the upgraded profitability would turn out as it follows (Table A2.2):

Table A2.2 Price per energy unit (Mongird et al. 2019) and calculated rate P'.

Type of battery	P ($\$ \cdot kWh^{-1}$)	P' ($\$ \cdot kWh^{-1} \cdot cycle^{-1}$)
Lead-acid	260	15,60
Li-ion NMC	390	25,07
Li-ion LFP	450	17,56

Based on these figures, arguably NMC should be discarded as a solution, and either LFP or Lead ought to be opted depending on other factors such as initial investment or available resources. In addition, it is expected that Lithium-ion prices significantly drop, while Lead-acid cost is decreasing more slowly, so probably LFP will be the best option in the long run.

A3. AGV models for battery energy estimation

These data (Table A3.1) have been used for estimating the approximate battery energy for different models that carry different loads and with different purposes but have also helped figure an essential outline of AGVs.

Table A3.1 Review of several reviewed AGV models.

AGV name	Weight (Kg)	payload (towed load)	Autonomy	(Wh)
Matthews AMR	73	70	6-8h	412
OTTO 100	127	100	Continuous operation with ~85% individual vehicle availability (Enterprise policy)	1104
OTTO 1500	525	1500		5120
ROBOS RBS-T1	450	(1000)	9h	5280
Sharp AGV	-	200 (500)	8h	1008
Waypoint Vector	-	272	8h plus	1000
Waypoint Mavek	-	1360	8h plus	4000
NOVUS Carry AMIR 100	100	100 (300)	-	1198,8
MIR100	70	100 (300)	10	960

MIR200	70	200 (500)	10	960
MIR250	83	250	13	1631,34

A4. Weight estimation

The total weight will be the sum of all its parts:

A3.1 Battery (heaviest case)

Lead-acid battery 1,6 kWh, equal to four 400 Wh, 11,5 kg batteries, total weight: 46 kg

A3.2 Battery (lightest case)

LFP battery 1,3 kWh: 16 kg

A3.3 Frame (steel)

Cheira (2019): 25 kg

Studied frame: Roughly 20-22 kg

A3.4 Motor and transmission

Approximately 6 or 7 kg (500w, 24V DC Gear Motor 500 RPM (0.67 HP), n.d.)

A3.5 Traction wheels

Depending on diameter, ~5kg each.

A3.6 Caster wheels

Somewhere under a kilogram, roughly 0.7 kg (*Castors and Wheels Catalogue 151.RE* 2013)

A3.7 Electronics and sensors

Around 15 kg.

A3.8 Bodywork

Around 15 kg.

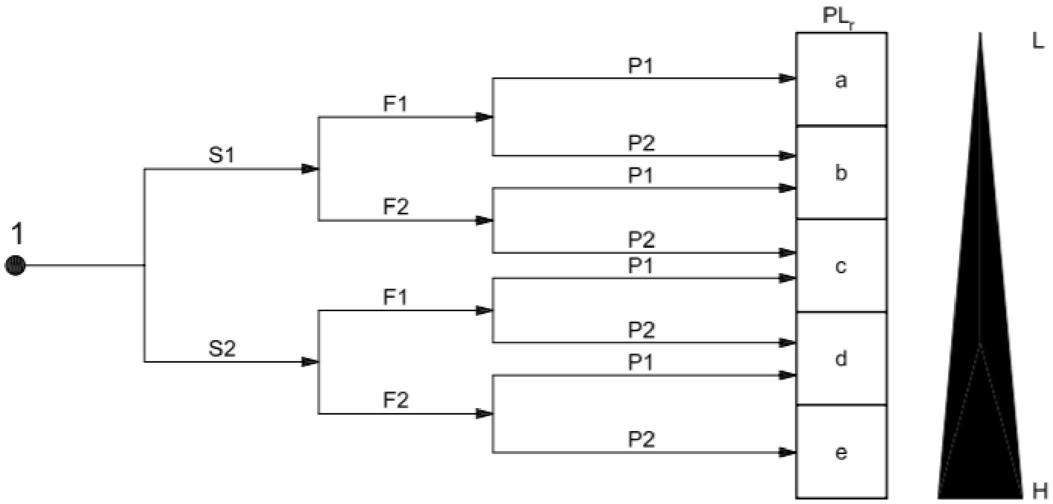
A3.9 Total weight

If the parts are added congruently (there are two traction wheels and two caster wheels), the mass of the vehicle rises to 141.4 kg in the heaviest case, and 111.4 for the lightest.

When the AGV works as an underride as well, the maximum load is raised by 100 kilograms, making it 241.4 when lead-acid batteries are used, and 211.4 with LFP.

A5. SS-EN ISO 13849-1:2016

This standard is a widely used one, particularly in safety designations. In short, the safety function of any given system can be categorized within a performance level (PL_r) depending on three risk parameters (Figure A5.1). These PL_r delimitate the safety measures the system will equip.



Key

1 starting point for evaluation of safety function's contribution to risk reduction
L low contribution to risk reduction
H high contribution to risk reduction
PL_r required performance level

Risk parameters:

S severity of injury
S1 slight (normally reversible injury)
S2 serious (normally irreversible injury or death)
F frequency and/or exposure to hazard
F1 seldom-to-less-often and/or exposure time is short
F2 frequent-to-continuous and/or exposure time is long
P possibility of avoiding hazard or limiting harm
P1 possible under specific conditions
P2 scarcely possible

Figure A5.1 Graph for determining required performance level for safety function. Source: SS-EN ISO 13849-1:2016

A6. SS-EN 1175:2020

The electronic features of industrial trucks are listed in this standard, as required by SS-EN ISO 3691-4:2020. The type of truck is, according to the definition within this own document, industrial tractor, so only the measures for this sort of vehicle have been gathered. In addition, owing to the extensiveness of this document only these latter features have been listed.

Table A6.1 Performance levels for each issue for industrial tractors. Source: SS-EN 1175:2020

Clause	Reference chapter	PLr for industrial tractors
4.5.2	Travel control system	c
4.5.3	Monitoring of operating position	b
4.5.5	Automatic restoration of drive system	a

4.5.6.2	Uncontrolled acceleration from standstill on level ground	c
4.5.6.3	Unintended truck behaviour while truck is moving	b
4.5.8	Electrically/electronic controlled service brake	c
4.5.9.1 a	Automatic release of parking brakes	c
4.5.9.1 b	Automatic activation of parking brakes at standstill	b
4.5.9.1 c	Automatic activation of parking brakes on a ramp	b
4.5.9.1 d	Detection of failure of automatic parking brakes	a
4.5.9.2	Trucks without automatically appliedparking brake	a
4.5.9.3	Indication of parking brake state	a
4.5.10 g	Speed limitation for operation fromoutside the truck	c
4.7.2.2 a	Unintended steeringwithout backup	d
4.7.2.2 b	Unintended steeringwith backup	c
4.7.2.3	Supervision of steering system	c
4.7.2.4	Backup steeringwarning	a
4.7.2.5	Deviation fromsetpoint	c
4.7.3	Electrically poweredassisted steering systems	a
4.3.7	Overcurrent protection	b
4.4.2.1	Battery charging	b
4.4.2.2	On board charger and/oradditional components	b
4.9.1.2.1	Initiation of stopping ofhazardous movement	c
4.9.1.2.2	Interruption of powersupplies	b
4.9.2.3 a	Decoupling caused by fault	c
4.9.2.3 b	Decoupling whiletravelling	b
4.9.2.5	Interlocking of guards	b
4.9.2.6	Unauthorised starting	a
5.3.4	Detection of frame fault	b

A7. SS-EN ISO 3691-4:2020

This standard is in charge of gathering and evaluating the risks of industrial driverless trucks. During the first chapters the introduction, scope, definitions and references (in which the previously studied EN 1175:2020 is addressed). Afterwards, the safety requirements are illustrated and labelled in PL_r (Table A7.1). Some other special measures are imposed, for instance towing trucks (i.e. tuggers) must visually and acoustically signal not less than 2 s and limit its speed to 0,3 m/s during the first 5 s or the distance between truck and cart plus 0.5 m. This are mainly programming demands and as a result are not treated in this study, as it is hardware minded. Later on, the verification of safety measures is presented and a guide on how to display the information for use, which again exceed the scope of the project.

Table A7.1 Performance levels imposed for driverless trucks. Source: SS-EN ISO 3691-4:2020

Description of the safety function (or a part of safety function)	Main risk	Note	PL_r
Braking system control	Collision with persons	PL function controls the deceleration function.	d

Parking braking system control	Unintended motion of the truck: risk of collision Reduction of braking performance if the battery is disconnected (unlikely)	PL function controls that brake is dis-engaged in order to avoid continuous braking when travelling. (Wear and release of the brake to be checked with periodic maintenance).	b
Over speed detection system (speed > truck rated speed)	Collision with person. Personnel detection not efficient due to over speed.	PL Monitor that truck speed is not over the maximum rated speed. In case of malfunction, an emergency stop shall be activated.	c
Speed monitoring in case of speed <0,3 m/s			c
Adaption of the sizes of the safe detection fields of an ESPE for linear movements. (e.g. forward direction, backward direction, lateral and crabbing directions.)	Collision with person. Personnel detection not efficient due to different speed vs personnel detection	Assure that the personnel detection field is consistent with actual truck speed. Travel speed monitoring can be performed by the personnel detection means. If PL=d cannot be attained speed shall be reduced to a maximum of 0,3 m/s.	d
Adaption of thesizes of the safedetection fieldsof an ESPE in turning and pivoting. No speed limitation in the related direction of travel.		No speed limitations	d
Adaption of the sizes of the safedetection fields of an ESPE. For additional side fields in the turning andpivoting when truck speed is limited at 0,7 m/s in therelated directions of travel (xand/or y) (side speed).	Collision with aperson in case a wrong safety measure is selected	All information needs to achieve the PLr. Assure that the personnel detection fieldis consistent with actual truck speed. Travel speed monitoring canbe performed by the personnel detection means.	c
Deactivation ofcharging connections	Electrical risk	For truck charging pointsthey shall be disconnected prior to the truck traction movement.	b
Checking if the load is in the in-tended position	Unintended fallof a load Loss of stability Undetected personnel	Only if a potential safety risk can appear: if anunintended position of the loadoccurs, a protective stop shall be activated.	b See NOTE.
Load handlerposition and motion	Unintended event (e.g. fall of a load)	Only if a potential safety risk can appear: If anunintended position of the loadoccurs, a protective stop shall be activated.	b See NOTE.
Avoiding instability caused by speed, steering and load handling	Stability of the truck	Only if a potential safety risk can appear: PL control combination among stability parameters (e.g. steering speed, traction speed, load handling) are within the stability requirements.	c
Stop hazardous movements and functions	Intended emergency stop by a person	Emergency stopof the truck traction and brake Stop of all movements	d

Stop the truck following the detection of a person in the direction(s) of travel	Collision with person	Protective stopof the truck after the detection of a personin the path	d
Stop the truck following a person detection with inadequate clearance	Collision with person	Assure the personnel detection zone, thebumpers or virtual bumpers, covers the free space between the truck and the fixed closed structure, to within 180 mm from the fixed closed structure.	d
Override of the personnel detection meansin manual mode or maintenance mode	Collision with person	May require PL=d due to links to other functions thatrequired PL=d	c
Muting of the personnel de-tection means	Collision with person	In the automaticmode, muting of the personnel detection meansis not possible for a speed >0,3 m/s.	d
Stop of the truck from the load end	Crushing a person	Protective stop of the truck after the detection or theemergency stop actuated.	d
Conditional selection of Personnel Detection Means protected zones	Collision with person	Selecting the correct field can be depending on several conditions (Loaded/ unloaded; narrow load/wide load; different zones).	d
Conditional selection of Personnel Detection Means protected zones for additional side fields in the turning and pivoting when truck speed is limited at 0,7 m/s in the related directions of travel (x and/or y) (side speed).	Collision with a person	Selecting the correct field canbe depending on several conditions (Loaded/ unloaded; narrow load/wide load; different zones).	c
Detection that a rider which is intended to rideon the trucks remains in the intended position.	Fall of the per-son or cutting risks	If the rider leaves the in- tended position,the truck shall initiate a protective stop.	d
“Hold to run” function (except the automatic mode)	Fall of the load or cutting risks due to unexpected movements or collision with aperson	No movement if the “hold to run” control is not actuated	c
Where trucks are not de-signed to have automatic operation with an operator or rider mode, andprovision is made for an operator position, the presence of the operator shall deactivateall automated functions.	Fall of the person or cutting risks	If personnel are on the truck in arider designatedposition, the truck shall initiate a protective stop.	c
Tiller position in the automatic mode	Collision withperson	If the tiller is notin a rest position, the truck shall stop.	c
Optical, acoustical signals/ systems	—	—	a
Perimeter guarding	Collision withperson	Personnel detection means ofa stop	d

As for the appendices, Annex A is a normative on how to prepare the zones in the factory, Annex B an informative compilation of all the possible hazards, corresponding the respective standard heading.

Annex C is a normative concerning forklift capacity, thence off-the-point, Annex D on the load-transfer operations and lastly Annex E condenses the verification method of each standard subclause in a table, both of which are not covered either.