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# Analysis of LGV usage for the improvement of a customized production

Paolo Cicconi[a*], Roberto Raffaeli[b], Leonardo Postacchini[c], Andrea Monteriù[c], Emanuele Pallotta[c], Mariorosario Prist[c], Filippo Emanuele Ciarapica[c], Michele Germani[c]

[a]*Università degli Studi Roma Tre, via della Vasca Navale 79, 00146 Roma, Italy*
[b]*Università degli Studi di Modena e Reggio Emilia, Viale A. Allegri 9, 42121 Reggio Emilia, Italy*
[c]*Università Politecnica delle Marche, via Brecce Bianche 12, 60131 Ancona, Italy*

* Corresponding author. *E-mail address:* paolo.cicconi@uniroma3.it

**Abstract**

The paper describes an approach for analyzing the use of a Laser-Guided Vehicle (LGV) in the context of the small and medium-sized enterprise. The use of LGVs is an efficient solution to provide more flexibility in the context of Just-In-Time production; however, the investment cost can limit this application. A methodology has been proposed in this work to analyze the technical feasibility of using an LGV in the manufacturing industry of customized products. The test case focuses on the study of a laser-guided system to optimize the handling of molds for customized production. In this scenario, an LGV is proposed to substitute manual carts used for moving molds from the warehouse to the injection machines. The traditional path included an intermediate station for pre-heating the molds in hot-air ovens. The proposed solution includes the study of an induction heating system on the LGV to optimize time and energy consumption.

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*Keywords:* Laser Guided Vehicle; System modeling; Customized production; Life Cycle Cost.

## 1. Introduction

Industrial processes are characterized by the necessity to handle materials that are required as input to the manufacturing activities or are produced by the processes themselves. The necessity to lower production costs to be competitive on the market forces companies to make saves on labor costs. In this context, material handling is one of the major sources of possible savings, especially in most developed countries where wages are relatively high. Industry 4.0 technologies offer many possibilities to tackle this problem. Automation and additive manufacturing technologies are connected to the possibility of reducing direct human employment in processes. Logistics is another major field of intervention. Indeed, automated material handling solutions aims also at improving work conditions, alleviating people from tiresome and not motivating tasks.

Even if the direct cost of material handling is difficult to be estimated, some scholars claim that it can achieve around 20-25% of total manufacturing cost [1]. The main factors which contribute to increasing this direct cost are wasted time and labor cost. Generally, material handling does not add value to the product because it is not a production process [2]. Therefore, the warehouse automation is an issue that has been attracting the attention of both scientists and practitioners for several decades [3]. In this context, the employment of Laser Guided Vehicles (LGVs) can improve the system flexibility with a short pay-back period [4]. These systems are cost-efficient, they can improve productivity and address the issues related to the labor cost [2]. Unmanned guided vehicles have been replacing human-driven forklifts and traditional internal logistic vehicles [5].

An LGV is an automated and programmable mobile vehicle, which is very similar to an Automated Guided Vehicle (AGV), but the navigation is laser-guided. These unmanned guided vehicles are used in industrial applications to move material into a manufacturing facility after selecting a certain path [1].

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Speed and steering commands are regulated by the controller of the LGV's system which also implements the manufacturing environment and the map of paths.

Nowadays, the simulation of the warehouse is a common activity for supporting the design process, the evaluation of the whole system capacity, and the identification of bottlenecks [6]. The simulation aims at supporting the design of the warehouse considering flexibility, modularity, and adaptability. Moreover, companies begin to use digital factory concepts in order to accelerate the designing process and eliminate the risk of wrong design [7]. One of the benefits is the possibility to redesign existing processes while optimizing operations. In this context, Wireless Sensor Networks are also used for the development of systems in smart factories elaborating data from sensors and testing [8].

Small and Medium-sized Enterprises (SMEs) demand for cost and energy-effective material handling; however, they need affordable solutions to proceed with such implementations. As already discussed by Kumbhar [2], an introduction survey should be analyzed before adopting or developing any type of material handling system. Therefore, factory visits and interviews with experts are necessary to implement such a virtual model of the manufacturing system based on a survey of production data [9]. To this end, one of the multi-criteria decision-making methods used in literature for selecting a material handling equipment is the Analytic Hierarchy Process [10].

The main limit to the widespread of such vehicles is the high initial cost related to equipment, software, paths, facility arrangement, loading-unloading stations, etc. [11]. The literature is lacking papers that analyze the life cycle cost of automatic handling systems for SMEs in customized production. While the performance of handling systems and the gains in terms of time and errors reduced have been already discussed, the investment cost and the pay-back period are not yet analyzed for LGV and AGV systems using an effective simulation model.

Batteries contribute to increasing the cost of LGV and AGV systems. Since such vehicles need a long time for battery charging, another battery or vehicle should be available to allow continuous operation of the manufacturing system during the charging period [12]. Even if Li-ion batteries are more expensive than traditional Lead-Acid ones, this technology is overcoming past solutions due to some advantages such as efficiency and longer lifespan [13]. Moreover, the cost reduction of Li-ion batteries can be improved using opportunity charging solutions and Lithium Titanium Oxide cells (LTO) [14]. This type of battery shows an important increase in terms of cycle life [15] and provides the possibility to frequently perform opportunity charging [16]. Moreover, LTO cells can be used in fast charging/discharging at a different range of temperatures and current rates [17].

The paper aims at supporting the technical and economic analysis of the usage of an automated guided vehicle in SMEs. A method is proposed including configurations, simulations, and analysis. The context regards customized production where variability and fragmentation require flexible and automated solutions. Since the cost of these solutions can limit their applications, the paper presents different use scenarios to highlight how the average number of in-logistic trips per working day can affect the life cycle analysis for ten years.

The remainder of the paper is organized as follows. Section 2 introduces the approach and the modeling of the LGV system. A test case is described in Section 3, and the results are given in Section 4. Finally, Section 5 reports the discussion and conclusions of the paper.

**Nomenclature**

| | |
|---|---|
| $a$ | acceleration, m/s$^2$ |
| $E$ | the electric field, V/m |
| $f$ | friction coefficient |
| $F_{moving}$ | the force for the LGV moving, N |
| $F_{friction}$ | the friction force, N |
| $G$ | the heat generated by Eddy current, J |
| $g$ | gravitational acceleration, m/s$^2$ |
| $J$ | the current density, A/mm$^2$ |
| $m$ | the total mass, kg |
| $N$ | the normal force, N |
| $R_{tot}$ | the total resistance force, N |
| $\sigma$ | electrical conductivity, S/m |
| $t$ | time, s |
| $v$ | velocity, m/s |

## 2. Approach

The approach for evaluating the usage of an LGV system in manufacturing is described in Fig. 1. The parametric model of the LGV system has been defined and simulated in MATLAB/SIMULINK®. This virtual model reproduces the performance and analyzes time and energy consumption. The resistance forces, battery behavior, electrical motor, control system, and charging station have been considered when the LGV model has been defined.

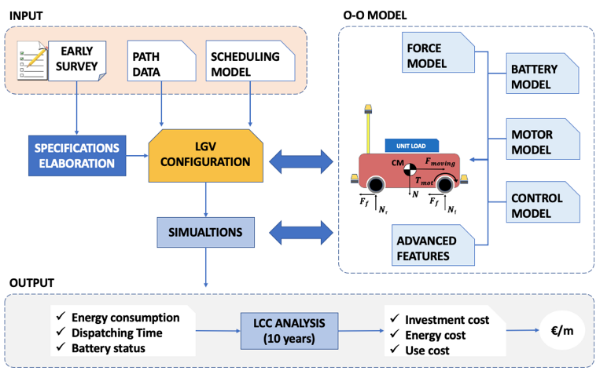


Fig. 1. The methodological approach for analyzing the feasibility usage of an LGV in production.

The input data of the proposed approach regards the analysis of the AS-IS system used for internal logistics. An early survey activity is proposed for supporting the gathering of information to define the specifications. In this context, interviews with experts are useful for evaluating the possible usage of the LGV system into the internal logistics environment. The data about the internal logistic path and the relative scheduling model complete the required input for the proposed analysis.

Input and specifications are elaborated and formalized into a tool called LGV CONFIGURATION which interacts by parameters with the Object-Oriented (O-O) modeled into MATLAB/SIMULINK®. This level enables the configuration of the LGV by defining its main functional groups such as frame, battery, traction motor, and control system. An Object-Oriented (O-O) model has been implemented to simulate the dynamics of the automatic LGV vehicle.

The outcome of the proposed approach is the technical and economic analysis in terms of energy consumption, dispatching time, and Life Cycle Costing (LCC). The LCC analysis is here implemented as a Total Cost of Ownership (TCO) calculated in 10 years.

### 2.1. Force modeling

Equation (1) describes the total resistance force related to an internal logistic vehicle when it is moving. This force is a sum of two forces, namely the driving ($F_{moving}$) and the friction one ($F_{friction}$).

$$R_{tot} = F_{moving} + F_{friction} \tag{1}$$

The term $R_{tot}$ represents the force required to move any internal logistic vehicle under these assumptions: none floor irregularities, flat paths (absence of any uphill and downhill), and neglection of aero drag due to slow velocity (about 0.5-1.5 m/s). Therefore, the analyzed forces are the friction resistance of the wheels (2) and the resistance to moving in the inertial frame of reference (3).

$$F_{friction} = f \cdot N \tag{2}$$

$$F_{moving} = m \cdot a = m \cdot \frac{dv}{dt} \tag{3}$$

$$N = m \cdot g \tag{4}$$

The friction force is equal to the normal force ($N$) multiplied by the friction coefficient ($f$) between wheels and the floor. The term $N$ is equal to the total mass ($m$) multiplied by the gravitational acceleration ($g$), as described in (4). The resistance force to moving the internal logistic vehicle is described in (3) as the total mass ($m$) multiplied by the acceleration ($a$), evaluated in $m/s^2$.

### 2.2. Battery modeling

This paper considers the use of LTO cells and opportunity charging strategies for the implementation of LGV applications in the industry. The battery modeling and simulation is necessary for analyzing the range of the storage unit and the charging time in operative conditions. The outcome of this analysis gives feedback about the sizing and performance of the configured battery pack.

Fig. 2 describes the equivalent *RC* circuit model [18] used for modeling a Li-ion cell. In this circuit, *Ri* represents the equivalent ohmic internal resistor and *R0* // *C1* is the resistor-capacitor parallel network. The component *R0* is the equivalent polarization resistance and *C1* is the equivalent polarization capacitance that simulates the transient responses during charging-discharging. These parameters (*Ri*, *R0*, and *C1*) are constants that depend on the specific Li-ion cells employed in the configuration.

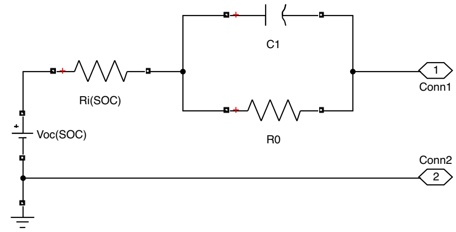


Fig. 2. Equivalent circuit of a single cell.

A Li-ion battery consists of several cells, which are rechargeable elements. A set of Li-ion cells can be connected with serials and parallels to define a battery pack [14]. Fig. 3 describes an example of a battery layout of 2 parallel rows by 12 cells (for a total of 24 cells).

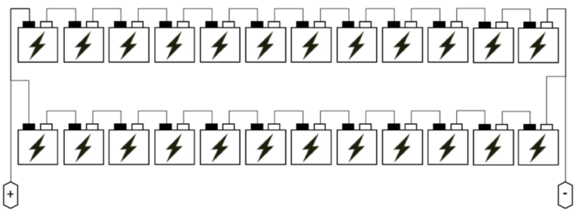

Fig. 3. Scheme of a battery layout with 24 Li-ion cells.

### 2.3. Motor modeling

A typical automated vehicle for internal logistics is equipped with a driving and steering wheel group positioned on the central axis of the vehicle. The drive and steering wheel group is made up of a load-bearing mechanical structure in which a motor is inserted in a dedicated gearbox. Generally, the electric motors used are AC asynchronous motors equipped with electric braking (5Nm, 24V).

This type of motor has been simulated using MATLAB/Simulink®. A Proportional Integral Derivative (PID) Controller has been considered to maintain the desired velocity during the simulation of the dispatching phase.

The motor modeling and simulation is important for analyzing the LGV power consumption. The analysis of the simulation results gives feedback when it is moving on its path during the dispatching phase and consequently the size of the configured battery pack.

### 2.4. Mold heating modeling

An industrial LGV can be customized with advanced features that depend on the specific application. As an advanced feature, this paper describes an induction worktop of the molds heading and this section introduces the approach for modeling such a system.

The induction heating concerns the energy losses due to the Joule effect and the energy losses associated with magnetic hysteresis. Maxwell equations describe this electromagnetic phenomenon [19].

The heat ($G$), generated by eddy currents, can be calculated using Equation (5). In this equation, the losses introduced by magnetic hysteresis are not considered because their contribution is much less than eddy current heating [20]. While the term ρ is the electrical resistivity, the term $J$ is the free current density. Equation (6) describes how $J$ is related to the electrical conductivity ($\sigma$) and the electric field ($E$).

$$G = \rho |J|^2 \tag{5}$$

$$J = \sigma E \tag{6}$$

The electromagnetic model has been solved in Matlab/SIMULINK® to estimate the active power generated by the Joule effect due to eddy currents on the ferromagnetic plate of a mold to be heated.

## 3. Test Case

The test case describes the feasibility analysis of the LGV usage for improving the internal logistics in customized production. The proposed analysis is focused on a medium-sized company employed in the customized production of footwear soles. In this manufacturing scenario, there are 8 rotary machines for the foaming of soles. Each machine can produce about 80 soles per each machine-lap. The company needs to continuously replace a variable number of molds on the basis of the customers' orders. These orders are fragmented in terms of product sizing and type.

The study describes a technical-economic analysis to compare a traditional dispatching solution with manual carts with an automated solution based on the usage of an LGV vehicle.

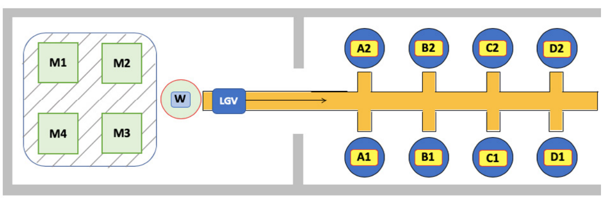


Fig. 4. The manufacturing layout with the mechanized warehouses (M1, … M4), LGV, dock stations (W), and molding machines (A1, A2, … D1, D2).

The analyzed LGV is a three-wheel model with one wheel on the front part and two rear-ones. The front-wheel is a drive-one which also has a steering function for pivoting the vehicle. This drive-wheel has two electric motors. The first motor provides power for traction and the second one for steering. The prototypical LGV also has a worktop with four induction plates for the pre-heating of molds during their handling. In each mission, the LGV moves molds from the automatic and mechanized warehouse to the molding machines.

Fig. 4 shows the production layout that has been analyzed. There are 8 molding machine stations (A1, A2, … D1, D2), 1 dock station for the LGV loading/unloading and charging (W station), and 4 mechanized warehouses with molds (M1 – M4). Each time a workstation needs to be set with a new mold, the central system receives a call and a robot picks up the mold in one of the warehouses and brings it to station W. Here is where the LGV is waiting, recharging itself and pending to be loaded. Once the LGV is loaded, it starts heating the mold and moving towards the workstation.

Table 1. Matrix with all path distances (evaluated in meters) between each workstation.

| | W | A1 | A2 | B1 | B2 | C1 | C2 | D1 | D2 |
|---|---|---|---|---|---|---|---|---|---|
| W | - | 80 | 80 | 95 | 95 | 110 | 110 | 125 | 125 |
| A1 | 80 | - | 15 | 20 | 20 | 35 | 35 | 50 | 50 |
| A2 | 80 | 15 | - | 20 | 20 | 35 | 35 | 50 | 50 |
| B1 | 95 | 20 | 20 | - | 15 | 20 | 20 | 35 | 35 |
| B2 | 95 | 20 | 20 | 15 | - | 20 | 20 | 35 | 35 |
| C1 | 110 | 35 | 35 | 20 | 20 | - | 15 | 20 | 20 |
| C2 | 110 | 35 | 35 | 20 | 20 | 15 | - | 20 | 20 |
| D1 | 125 | 50 | 50 | 35 | 35 | 20 | 20 | - | 15 |
| D2 | 125 | 50 | 50 | 35 | 35 | 20 | 20 | 15 | - |

At the workstation, the LGV stops heating the mold and is unloaded and then loaded back with the mold that has been replaced. The LGV then moves back to the W station where it is unloaded by the robot. Here the LGV puts itself into a charging mode, waiting for the next call. The LGV can transport a total of 2 pairs of molds and, with proper scheduling, it can fulfill up to 2 calls with a single back and forth travel from the W station. For this test case, it has been assumed that, within one working hour, the LGV can receive from a minimum of 1 up to a maximum of 3 calls from the system. In order to cover the worst-case scenario for the scheduling of the mold change, it has been considered a situation in which there is no call scheduling and the calls are made only by the furthest stations from the W station (in terms of distance, see Table 1).

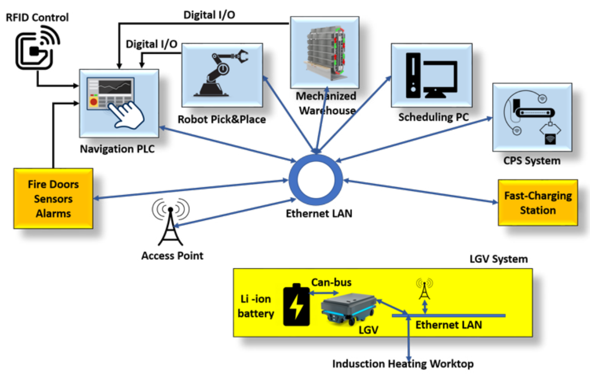


Fig. 5. The hardware architecture analyzed in this test case for the usage and management of the LGV vehicle in manufacturing.

The implementation of such an LGV solution requires the installation of a dedicated network of different components such as specific Programmable Logic Controller (PLC), sensors, wi-fi access points, etc. In fact, industrial applications require the interaction between other automatic systems such as mechanized warehouse, pick & place robots, automatic doors, etc. The study of an LGV system is related to the development of customized hardware and software architecture solutions. These solutions must be Industry 4.0 compliant to provide a higher level of management and control. According to these needs, Fig. 5 describes the architecture studied for the management of the LGV vehicle analyzed in this test case.

### *3.1. Mold heating*

The mold heating system has four induction plates placed on the LGV's worktop. This induction system is used for heating molds used for the production of polyurethane footwear soles (Fig. 6). This industry employs mixtures of polyether polyols that are fast to react. However, such mixtures are liquid at room temperature and they need specific conditions for foaming. The wall temperature into the mold cavity should be around 40-50 °C to obtain a good quality foaming. Therefore, molds are generally preheated with hot air ovens to avoid defects in the first molded pieces [20]. Here, the induction heating system replaces the employment of 15-kW hot air ovens. The induction heating system has been selected because fast and efficient [21]. This system can heat a mold in a few minutes reducing the long heating time due to the use of hot air ovens. The electromagnetic high-frequency induction is an efficient way for the non-contact heating of the mold walls. The electromagnetic field is generated by a coil which induces eddy currents on the ferro-magnetic part. These currents can heat the ferromagnetic part at various depths by the Joule effect.

The analyzed mold consists of a steel base plate and an aluminum block with a bottom part and a top one (Fig. 6). The contact between the bottom and top part forms the shape of the sole's cavity to be foamed. The walls of the cavity must be maintained at the defined range of temperature (40-50 °C) to avoid defects in manufacturing. The aluminum block of the mold is not heated by induction but by thermal conduction. Since aluminum is not a ferromagnetic material, the eddy currents of the induction system are applied for heating the ferromagnetic steel base of the mold. The steel plate can even achieve a temperature of 80-100°C in a few minutes. Then, the hot steel base exchanges the heat by thermal conduction with the aluminum block.

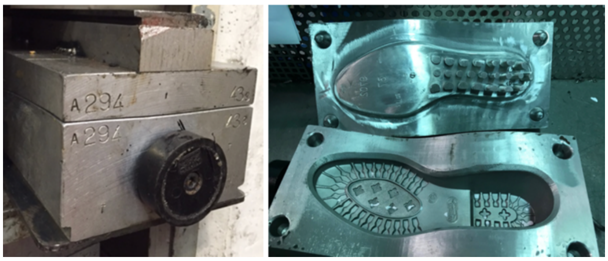


Fig. 6. Example of molds for footwear soles.

### *3.2. Battery sizing*

The battery configuration has been defined after the early analysis of energy consumption. This battery unit has a capacity of 2 kWh and employs LTO cells (Table 2). This type of cell can provide high C-rate in discharge and discharge [22]. A continuous 4-C rate has been evaluated in simulations for charging and discharging. Due to this characteristic, a 2-kWh LTO battery can support a power peak until to 16 kW.

Table 2. Datasheet of the analyzed battery pack.

| Characteristic | Value |
|---|---|
| Cell type | Lithium Titanium Oxide (LTO) |
| Cell voltage | 2,4 V |
| Cell capacity | 20 Ah |
| Number of cells | 44 |
| Battery Capacity | 40 Ah |
| Battery Energy | 2 kWh |
| Fast charging | 4-C rate |
| Battery weight | 34 kg |
| Cycle life | 20.000 |

### *3.3. Cost data*

This section describes the assumption and cost data used for the development of the proposed technical-economic analysis. The comparison is between two solutions.

The traditional solution (AS-IS) includes manual carts pushed by an operator which puts the molds the day before into a hot air oven before putting them on the foaming machine. The hot air oven has a nominal power of 15 kW and it is used for mold heating.

Table 3. Cost data related to the AS-IS case with manual carts and oven (without LGV).

| Description | Cost |
|---|---|
| hourly operator cost | 14 €/h |
| Energy cost per kWh | 0,17 €/kWh |

Table 4. Cost data related to the TO-BE case with LGV for molds handling and heating.

| Description | Cost |
|---|---|
| LGV Vehicle | 80.000 € |
| Network (Lan + Wi-Fi) | 15.000 € |
| LGV Installation (path and PLC) | 10.000 € |
| CPS Development Kit | 10.000 € |
| Mold Heating - worktop | 10.000 € |
| PC - Scheduling System | 10.000 € |
| Wireless Charger (3,6 kW) | 10.000 € |
| General Maintenance (3%) | 4.350 € |
| Li-ion Battery (2 kWh - LTO) | 1.800 € |

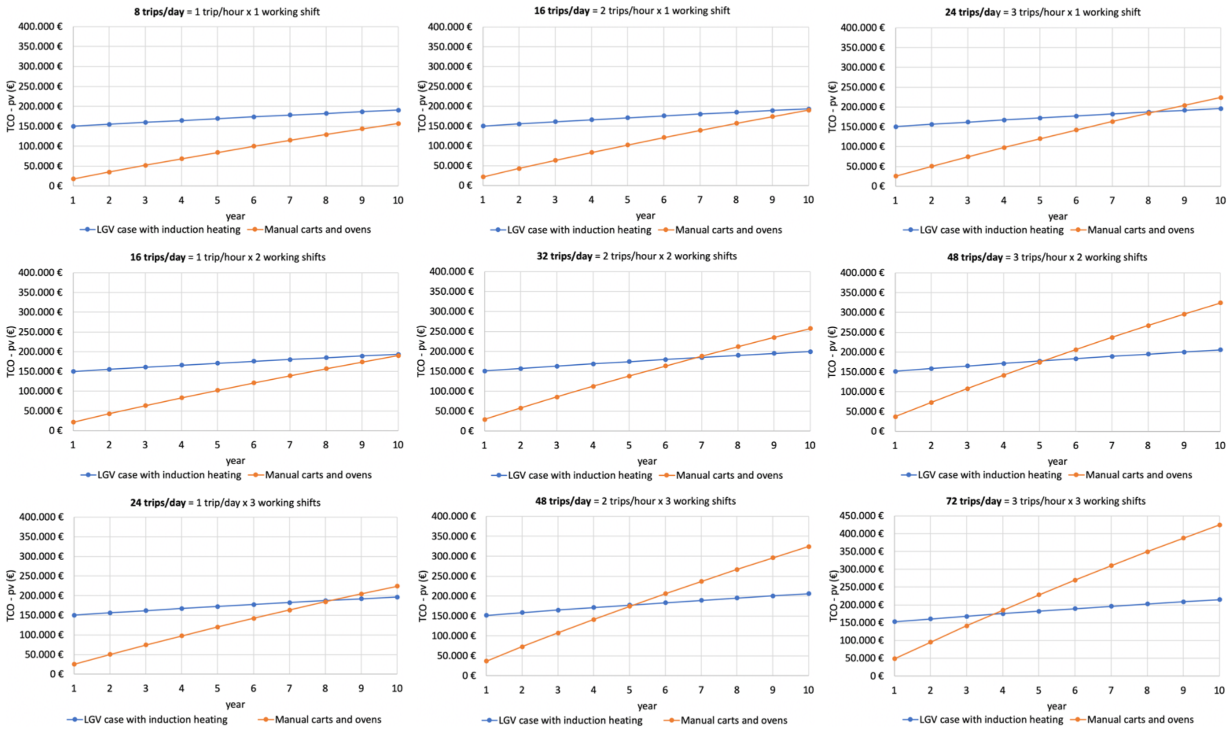


Fig. 7. The comparison of different breakeven scenarios in terms of trips per day and working shift. The blue lines represent the LGV case with the induction heating for molds; the orange lines represent the case of manual carts and ovens for mold heating.

The new solution (TO-BE) includes the employment of an LGV which can heat four molds per time during each trip by induction heating. Both solutions (with and without LGV) includes the use of a mechanized warehouse for molds storage. As an assumption, the cost of ovens, carts, and mechanized warehouse units are not considered into the proposed LCC comparison. Table 3 and Table 4 describe the cost data used for analyzing each scenario in terms of LCC. The cost data reported in these tables are related to the Italian market.

## 4. Results

The results of the system simulation have been analyzed in terms of energy consumption. The comparison has been performed in terms of LCC between the traditional dispatching method (with manual carts and heating ovens) and the new system which implements LGV with the induction heating of molds.

Table 5 reports the energy consumption simulated for the LGV dispatching. The analysis of the energy consumption includes the main functional units such as “Mold Heating”, “Moving and steering”, and “PLC, sensors, and controllers”. The energy consumption due to PLC and other onboard systems has been estimated by analyzing the specifications of the equipment.

The energy consumption related to a single round trip is due to the path length and the difference between the mold temperature, the target value, and the room temperature. The longest path is about 250 m (a round trip with 8 corners). As an assumption, the max speed of the LGV vehicle has been considered as 1 m/s in these simulations. Therefore, considering this data and the temperature worst-case scenario for the mold heating, the energy consumption can achieve until 810 Wh per trip. Considering a fast charging current of 4-C rate for the proposed battery, the battery pack can be charged with a quantity of 810 Wh in 15 minutes with a charging power of about 3,2 kW.

Table 5. The report about the average energy consumption related to each LGV functional unit of the LGV vehicle.

| Functional unit | Energy consumption | Description |
|---|---|---|
| Mold Heating | 125 Wh (per mold) | The specific energy consumption for heating one mold from the boundary temperature of 18°C to 45°C in about 120 s; |
| Moving and steering | 1,1 Wh/m | The specific energy consumption calculated for an average round trip (210 m, 8 corners, 120 s); |
| PLC, sensors, and controllers | 500 Wh | The hourly consumption of the on-board equipment; |

Different life cycle scenarios have been evaluated to assess the economic benefits/drawbacks of replacing a manual handling system with the automated LGV vehicle in the analyzed test case. The life cycle analysis has been evaluated over 10 years considering a discount rate of 3%. A different combination of working shifts and trips have been evaluated to better understand the convenience and the economic sustainability of such automation.

As reported in Fig. 7, the analyzed parameters the number of the working shifts and the number of trips per day. Each mission considers a round trip for dispatching 4 molds. The greater the number of trips is, the closer is the breakeven point because the breakeven point of such investment depends on the number of trips dispatched per year.

Analyzing the highlighted report, if the dispatching is less then 24 trips per day, the automated LGV vehicle is not a convenient economic investment in 10 years for the proposed case study. On the other hand, if the number of trips increases up to 72 trips per day, the breakeven point is expected to be reached at the end of the third year (before the fourth year). In this case, the implementation of such an LGV system could be a feasible and good investment.

As a result of the life cycle analysis, Fig. 8 reports the comparison in terms of specific cost per meter (€/m) related to the usage of the LGV vehicle in different conditions of the number of trips per day and working shift. The histogram shows a comparison related to the number of working shifts and the number of trips per day (Fig. 8).

Focusing on the specific context of customized, variable, and season production, a small and medium-sized industry continuously changes its production scheduling to respond to the fragmented orders. The report proposed in Fig. 8 gives the possibility to contextualize the results for a different mix of production scenarios. The solution with 72 trips per day, elaborated in 3 shifts, is the most convenient because it achieves a specific cost of about 0,005 €/m. If the trips are 72, the analyzed industry can manage the substitution of about 288 molds per working day considering 4 molds dispatched per each mission. This value can be achieved in the context of a fragmented production with small batches per mold. However, in the case of a long-time scheduled production with large batches, the operative condition can require about 8-16 trips per day. In this second case, the cost per meter can be the fourth-time major or more.


Fig. 8. The result of the specific cost per meter (€/m) due to the LGV's usage for a different number of trips per day and working shifts.

## 4. Conclusions

The paper describes a simulation activity for the assessment of energy consumption and cost related to a specific LGV system for molds dispatching inside a manufacturing environment. Moreover, the paper gives information and data related to the investment cost for supporting such an automatic handling system. In particular, the specific test case also includes the heating of the molds when the LGV vehicle is moving. During a molding process, the necessity to maintain the walls of mold at the operative temperature requires an efficient and rapid technology, therefore the induction heating has been considered instead of the employment of traditional hot-air ovens. Since induction heating is fast, the waste time is also reduced in this phase.

The results show how the effective cost per meter of an automated guided vehicle in the industry is related to the number of trips dispatched per day. The range decreases from 0,045 €/m to 0,005 €/m if the number of trips increases from 8 to 72 per working day. The calculation has taken into account all components and equipment necessary for implementing such a system considering a lifetime period of 10 years.

A pay-back analysis has been assessed to evaluate if the operation of the LGV vehicle can be convenient if compared with traditional manual solutions. This is a practical and fast tool to give feedback about the quality of the investment. In particular, the proposed test case shows an advantage if the number of LGV's trips achieve a value between 48 and 72 missions per day.

As future work, the approach could include the employment of a fleet of LGV vehicles. The assessment could also include the comparison in terms of environmental indicators such as the equivalent carbon dioxide. The dispatching analysis could be based on a variable hourly demand instead of the worst-case scenario.

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