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A comparative analysis of different paperless picking systems

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Abstract

Purpose – Warehouse picking is often referred to as the most labour-intensive, expensive and time consuming operation in manual warehouses. These factors are becoming even more crucial due to recent trends in manufacturing and warehousing requiring the processing of orders that are always smaller and needed in a shorter time. For this reason, in recent years more efficient and better performing systems have been developed, employing various technological solutions that can support pickers during their work. The purpose of this paper is to introduce a comparison of five paperless picking systems (i.e. barcodes handheld, RFID tags handheld, voice picking, traditional pick-to-light, RFID pick-to-light).

Design/methodology/approach – Warehouse picking is often referred to as the most labour-intensive, expensive and time consuming operation in manual warehouses. These factors are becoming even more crucial due to recent trends in manufacturing and warehousing requiring the processing of orders that are always smaller and needed in a shorter time. For this reason, in recent years more efficient and better performing systems have been developed, employing various technological solutions that can support pickers during their work. The present paper introduces a comparison of five paperless picking systems (i.e. barcodes handheld, RFID tags handheld, voice picking, traditional pick-to-light, RFID pick-to-light.

Findings – The proposed approach contributes to the understanding of the performance of different technologies in different application fields; some solutions are more suitable for a low-level warehouse, others bring greater benefits in the case of picking from multilevel shelving.

Originality/value – The study concerns an issue that until now has received very little attention in the literature. It compares some traditional solutions with some innovative ones by an economic evaluation. The presented hourly cost function also takes into account the different errors arising and their probability of occurrence.

Keywords Hourly cost function, Paperless picking, Warehouse manual picking

Paper type Research paper

1. Introduction and background

The evolution of customer orders, which are becoming ever more frequent and require smaller amounts of products, has inevitably changed the way their processing is performed by suppliers, who are facing the need to respond very rapidly and flexibly. This trend strongly affects the configuration of picking warehouses and of the activities that have to be carried out within them, with larger pick volumes that have to be satisfied within shorter time windows (De Koster *et al.*, 2007; Bartholdi and Hackman, 2011). One of the priorities for warehouse managers is, therefore, the improvement of picking performance (Battini *et al.*, 2015). Considering that most of the order picking systems are characterised by manual activities performed by human operators, a possible approach for increasing the productivity of order picking systems could focus on pickers' productivity in terms of reducing the time needed to fulfil an

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order, and also the reduction of possible errors (Grosse and Glock, 2013; Grosse *et al.*, 2013). In the recent study by Grosse *et al.* (2015), "Proposition 1" underlines the importance of investigating other objectives besides travel time minimisation in an order picking system. In particular, the need to develop studies that focus on picking error reduction is pointed out including, for example, consideration of the precise possible trade-offs between the cost of investment in paperless information technology and the return on investment from reduced picking errors. Furthermore, according to De Koster and Van Der Poort (1998) and Poon *et al.* (2009), paperless order picking systems can be a useful strategy to obtain benefits in an order picking warehouse, as validated also in the case studies of some authors in the literature (Berger and Ludwig, 2007; Reif *et al.*, 2010; Yeow and Goomas, 2012). All these studies have concluded that a possible solution that would reduce picking errors and hence improve picking performances is the adoption of paperless picking technologies. According to Frazelle (1988) and Tolliver (1989), for example, it has been estimated that a light-directed picking system with automated data entry can reduce human error by 95 per cent as well as increase productivity by 10 per cent.

A paperless picking system is constituted of a set of devices designed and adopted to facilitate the work of the operators, mostly in terms of getting information on the product to be picked and finding the corresponding storage location (Guo *et al.*, 2014). The most traditional paperless order picking can be via mobile, handheld or with terminals and printers that are vehicle-mounted; however, a new frontier of paperless picking is represented by the use of important devices that have been developed to speed up picking activities and to avoid picking errors, such as LED displays or digital screens, voice-activated devices (voice picking), wireless appliances and lighting systems (pick-to-light). Pickers and warehouse staff are connected online with the warehouse information system, enabling updated stock information, immediate reactions to particular situations and the real-time monitoring of operational status, leading to an overall productivity increase. Once the decision to adopt a paperless system in a picking warehouse has been taken, the action that follows is the establishment of the technology that best fits the needs of the particular context being considered. In this sense, it is important to perform an accurate evaluation, which takes into account the technological characteristics of all the different systems, their practical features as well as their economic impact. Guo *et al.* (2014) proposed a study comparing three different paperless picking systems with traditional paper picking, while Iben *et al.* (2009) focused on the performances of different picking systems. However, very few contributions have reported evaluations of the economic aspects of the adoption of such solutions (Baumann *et al.*, 2012; Baumann, 2013).

This paper presents a comparative analysis of different paperless picking systems, and considers how the different characteristics of the devices impact on the picking time and on the error possibility. In particular, this analysis is conducted by means of a promising method based on the study of the hourly costs related to each paperless picking solution. Such a model can be used in a number of industrial contexts to help arrive at the most suitable paperless picking solution, taking into account the characteristics of the employed devices and of the warehouse. The remainder of this paper is organised in four sections. The next section introduces five different paperless picking solutions (handheld and barcodes, handheld and RFID tags, voice picking system, traditional pick-to-light, RFID pick-to-light), highlighting some their strengths and weaknesses together with a description of their functional characteristics. Then, in the third section, their economic evaluation is proposed through the development

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of a particular hourly cost function, which takes into account the systems' different characteristics, such as the technology employed, the fields of application, their performance and their limits, together with the different picking error probabilities. This cost function is then validated in the case study in Section 4, which concerns two different warehouse configurations. Finally, some further general considerations are considered in the conclusions.

2. Paperless picking technological framework

2.1 Presentation of the paperless picking technologies

Warehouse manual picking is considered to be one of the most critical warehouse activities; therefore, over the years many support systems have been developed to drive and control pickers during their work (Tompkins *et al.*, 2010; Guo *et al.*, 2014). One of the first devices adopted to facilitate the picking process, and also one of the most widespread, is the handheld barcode scanner. All the stock keeping units (SKU) or also just the stock locations are tagged with a barcode that is scanned by the operator during the picking of the SKU corresponding to the items on the picking list. In this way, the picking information is immediately communicated to the warehouse information system. Handhelds are often able to emit acoustic signals, too. This feature generally helps the user to understand whether the scanner has correctly read the barcode, but it can also be used to provide notification that the product scanned is exactly what the picker was expected to take. Such a system can be combined with paper picking lists, but picking lists can also be integrated directly into the handheld: once an item has been picked, the screen of the handheld shows the next product to be taken. Recently, handheld radio frequency identification (RFID) scanners have also become available. RFID is a technology that, due to its characteristics, has achieved great success in various logistics applications. RFID readers and tags can operate at three different frequencies: low frequency (LF; <135 kHz), high frequency (HF; 13.56 MHz) and ultra high frequency (UHF; between 850 and 960 MHz). LF systems are especially suitable for working near metals and water, even if they are characterised by small reading distances. HF systems, instead, typically have greater ranges and higher reading speeds, with the possibility of simultaneously reading multiple tags, although they can be influenced by the presence of metal objects. For warehousing and goods' tracking, UHF systems are more suitable: they have very high data transfer rates and long ranges (up to six metres), even though the signals typically do not pass through many materials (Battini *et al.*, 2009). The operating principle of RFID scanners is similar to that of barcode scanners, except that the SKUs or the stock locations are tagged with RFID passive tags instead of barcodes. The working frequency is mostly LF or HF; hence, the reading distances of the handhelds are small (Baudin and Rao, 2005; Hou and Huang, 2006; Karagiannaki *et al.*, 2011). In addition, and sometimes also as an alternative to such systems, other devices have been developed. They are often referred to as *poka-yoke* (literally "mistake-proof") solutions, because they perfectly reflect the principle according to which, in order to avoid mistakes, it is important to eliminate every chance of their happening (Baudin and Rao, 2005). The most widespread techniques are voice picking, also called pick-to-voice, and pick-to-light.

A voice picking system is a voice-directed device that uses speech recognition to allow warehouse operators to communicate with the warehouse management system. Pickers are equipped with a headset and a microphone to receive instructions about the picking by voice, and they verbally confirm their actions back to the system. The warehouse operator, for example, reads back the last digits of the item he has

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picked so that the system can check whether the correct item has been selected, then it can give the next instruction. On the other hand, in a pick-to-light system operators are guided by lights that are installed on the warehouse shelving. Each stock location has one light that turns on if the operator has to pick a corresponding product from that location. In order to complete every single pick, the picker has to press the button of the relevant stock location and, in some cases, also has to scan the barcode of the picked item. If more than one picker in the same warehouse area needs to work simultaneously, such system has to be integrated with paper picking lists, with digital displays or with handhelds, so that every picker can understand which lights are turned on for his or her order.

An evolution of the traditional pick-to-light is represented by the utilisation of RFID technology. An example of pick-to-light using RFID has been presented in 2011 in the *RFID Journal* (Friedlos, 2011). In the reported test case, RFID readers are installed at some points beneath the conveyor belt, while RFID passive tags are attached to the plastic buckets in which workers place the products required to fulfil the orders. When the bucket reaches an RFID reader point on the conveyor belt, this sends a signal turning on the lights of the required products, so that the operator can easily and quickly identify them. Another interesting application is represented by the pick-to-light system proposed by Andriolo *et al.* (2013): the operator wears a particular glove in which a UHF RFID reader is installed, so that he or she can easily perform the picks using both hands. On the racks on the other side, there are the UHF passive tags and a set of differently coloured lights. These lights can be turned on or off according to the picker's picking list by a proper centralised control system, which is also able to recognise whether the operator is accessing the right storage location or not, and it alerts the operator with a set of visual (or also acoustic) signals, preventing him or her from completing the wrong picking action. In this case, tag reading errors are avoided or adequately controlled through the proper adjustment of the RFID antenna, the choice of a good position for the RFID tags and the equipping of the warehouse with metal shelving. Furthermore, the correct reading of the tags is also warranted by the control system, acting on the received signal.

A new recent frontier for manual picking is represented by special glasses or head-mounted displays worn by the operator and reporting all the needed information on the lenses, making the picking activity easier (Weaver *et al.*, 2010; Guo *et al.*, 2014). Moreover, some companies are proposing automated pick-to-light configurations, in which picker's activities are fully assisted: even the progress and the stops of the picking cart are guided by the composition of the order.

2.2 Working schemes and functional comparison

In this section, the working schemes of the considered paperless picking systems are described, with a particular focus on the main activities that are typically performed during the picking process (getting information, searching, picking, confirming). In particular, during such activities different kinds of errors can arise, which, considering the impact of the whole process, can typically be distinguished as "detectable errors" and "propagating errors". The first of these categories can easily be intercepted, since the wrong item confirmation immediately advises the operator and allows the pick to be corrected; however, the second category of error is hidden and, hence, hardly recognisable, leading to further work at the end of the picking tour (Grosse *et al.*, 2013). Table I shows the errors considered to arise together with their proposed notation and description, and the actions needed to correct them. The four reported errors refer to the most common mistakes that can be made during the picking activity, as indicated in several literature contributions and also validated by the authors' practical experience (Poon *et al.*, 2009; Baumann, 2013; Guo *et al.*, 2014).

The usual operation of each of the considered paperless picking technologies has been analysed in order to identify a possible working scheme by which the four different actions are reported, together with the behaviour of the different picking errors (Figure 1). The sequence of the actions is always the same for all the systems; the only thing that eventually changes is related to the possibility of the simultaneous performance of some of them. In particular, for the barcode and RFID handhelds, all the activities from getting the information to the picking confirmation are done consecutively; however, for the voice picking system the physical picking and the confirmation are done together, because the operator can confirm the pick into the microphone while doing the other action. In the case of a traditional pick-to-light system, the information about the product to pick and the search of the stock location represent a unique activity since turning on the light allows the needed information to be immediately obtained and the right stock location to be identified. Furthermore, for the RFID pick-to-light system, the picking activity is also simultaneous with the confirmation since the RFID glove worn by the picker communicates with the centralised control system during the physical pick, without any further action being required by the picker.

As far as the errors arising are concerned, for the barcode and RFID handhelds all four kinds of error are present: the detectable errors e_1 and e_2 are recognised during the pick confirmation, which allows their immediate correction; for e_1 only the confirmation has to be repeated, while for e_2 the picking process has to be repeated completely. The propagating errors e_3 and e_4, instead, arise during the physical pick of the item but are intercepted only at the end of the picking tour. The same errors are present also for the voice picking systems, while for the traditional pick-to-light system the two detectable errors are missing; in fact, in this case it is impossible for the operator to confirm the picking of a wrong item since the light is obviously turned on only in the stock location corresponding to the right item. Finally, for the RFID pick-to-light system proposed by Andriolo *et al.* (2013), the errors e_1 and e_3 are not applicable, because the pick confirmation is immediate and always corresponds to the stock location from which the operator has picked the product; hence, such a system is characterised by the possibility of having the propagating error e_4, which refers to the picking of a wrong quantity of SKUs and of having the error e_2, even if this is detectable before the physical picking, thanks to the turning on of the red light.

Type	Notation	Description	Following actions
Detectable	e_1	Right item picked but wrong item confirmed	Confirmation of the right picked item
	e_2	Wrong item picked and wrong item confirmed	Wrong item stocked and right item picked
Propagating	e_3	Wrong item picked but right item confirmed	Wrong item stocked and right item picked (at the end of the picking tour)
	e_4	Wrong quantity picked	More items picked or extra items stocked (at the end of the picking tour)

Table I. Possible arising errors during a picking tour

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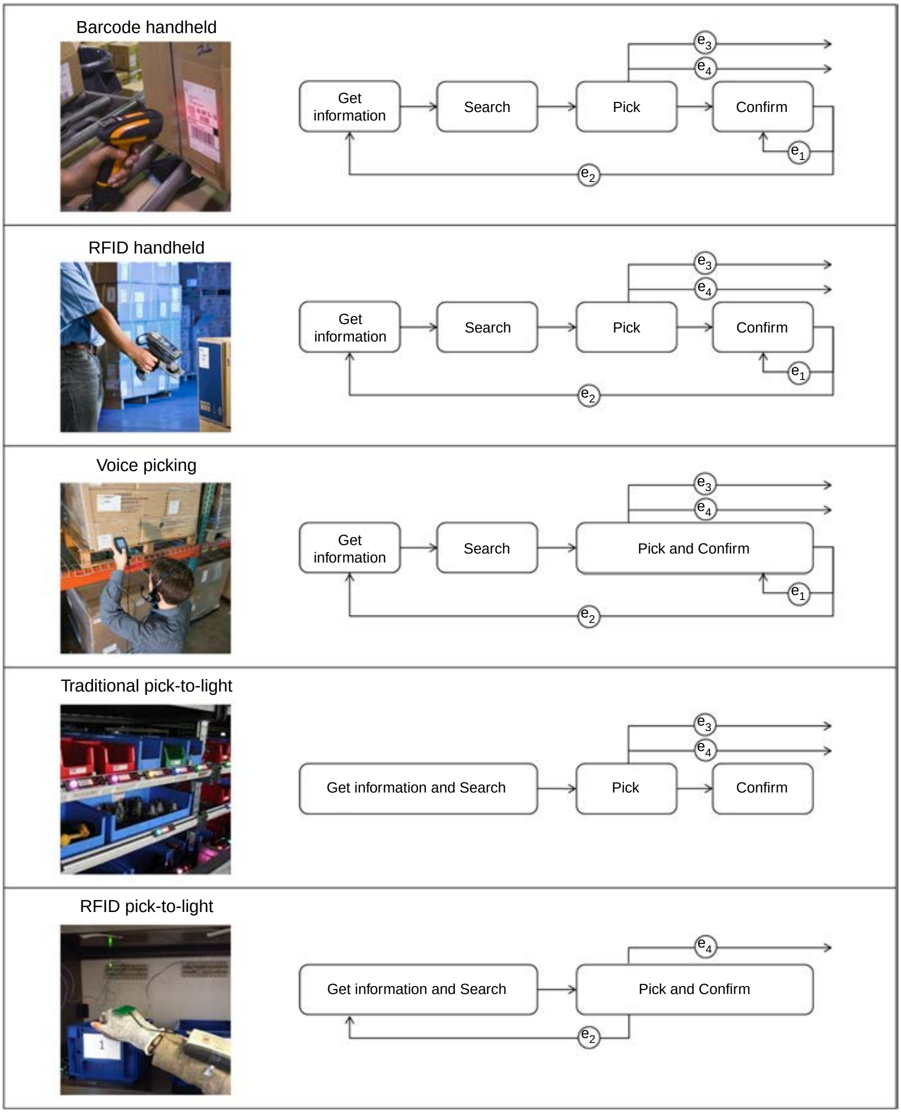

Figure 1.
High-level operating schemes of paperless picking systems

3. Economic evaluation of the different paperless picking solutions

Starting from the working schemes proposed in Section 2.2, a cost function is derived, which is useful from an economic point of view for conducting a quantitative comparison of the different paperless picking solutions (Baumann, 2013). This cost function, called the hourly cost function C_h^j, where j is the considered technology, comprises four main hourly cost components:

- Hourly cost depending on the number of stock locations, $C_{h,SL}^j$.
- Hourly cost depending on the number of pickers $C_{h,P}^j$.

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- Hourly cost depending on the picking errors $C^j_{h,E}$.
- Hourly fixed cost $C^j_{h,F}$:

$$C^j_h = C^j_{h,SL} + C^j_{h,P} + C^j_{h,E} + C^j_{h,F} \tag{1}$$

Considering the notations reported in Table II, the previous formula can now be set out as follows:

$$C^j_h = \frac{n_{SL} \cdot c^j_{SL}}{h_{SL}} + \left(c_{h,P} + \frac{c^j_{d,P}}{h_{d,P}}\right) \cdot \left\lceil \frac{n_R}{\dot{p}^j} \right\rceil + c^j_E \cdot n_R + \frac{c^j_F}{h_F} \tag{2}$$

where $\dot{p}$ is the picking rate, which is the number of performable picks per unit of time:

$$\dot{p}^j = \frac{1}{t^j_{tot}} \tag{3}$$

The corresponding picking time t^j_{tot} for each considered technology j can be expressed as the sum of two terms:

$$t^j_{tot} = t_{trav} + t^j_{net} \tag{4}$$

where the first addend t_{trav} represents the time needed for travelling and for getting on and off the picking cart, and the second, t^j_{net}, includes all the terms that depend on the used paperless picking technology j, according to the working schemes defined before:

$$t^j_{net} = t^j_i + t^j_s + n \cdot t^j_p + t^j_c \tag{5}$$

where t^j_i is the time needed for getting the information of the product to pick, t^j_s is the search time, t^j_p is the actual pick time, which also comprises the time for storing the picked product on the cart that is multiplied by the number of SKUs to pick n, and t^j_c is the confirm time (Schwerdtfeger *et al.*, 2011; De Koster *et al.*, 2007).

Cost component		Expression	Notation	Description
Stock locations hourly cost	$C^j_{h,SL}$	$\frac{n_{SL} \cdot c^j_{SL}}{h_{SL}}$	c^j_{SL} [€]	Stock location unitary cost[a]
			n_{SL}	Number of available stock locations
			h_{SL} [h]	Stock location devices total usage hours
Picker hourly cost	$C^{zj}_{h,P}$	$\left(c_{h,P} + \frac{c^j_{d,P}}{h_{d,P}}\right) \cdot \left\lceil \frac{n_R}{\dot{p}^j} \right\rceil$	$c_{h,p}$ [€/h]	Picker hourly cost
			$c^j_{d,P}$ [€]	Picker devices cost[a]
			$h_{d,p}$ [h]	Picker devices total usage hours
			n_R [$rows$]	Number of requested picking rows
			$\dot{p}^j$ [$rows/h$]	Picking rate[a]
Picking errors hourly cost	$C^j_{h,E}$	$c^j_E \cdot n_R$	c^j_E [€]	Error unitary cost[a]
			n_R [$rows$]	Number of requested picking rows
Fixed hourly cost	$C^j_{h,F}$	$\frac{c^j_F}{h_F}$	c^j_F [€]	Fixed costs[a]
			h_F [h]	Fixed elements total usage hours

Note: [a]Variable according to the considered technology j

Table II. Hourly cost function components and notations

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In fact, the paperless picking technologies do not influence all these time factors in the same way. Some of the factors are totally independent of the devices that are employed in the warehouse, such as the time spent in travelling from one stock location to another and getting on and off the picking cart. However, the actual picking time and the time for the storing of the product on the cart could be affected by the kind of device that it is used, taking account of whether the operator has both hands free or not; furthermore, such times are also influenced by the kind of product that is picked, its weight and volume. Finally, the time necessary to find the right stock location and the one needed to confirm the pick are the factors mostly influenced by the paperless picking technology being considered. For the scope of this paper, it could be concluded that it is sufficient to focus only on the time factors that depend on the device used. However, in the next sections it will be shown that, in order to conduct a complete cost evaluation, it is fundamental to consider also the travel time t_{trav}, which strongly influences the activities related to the error correction and differs also according to the considered technology (Table I). Furthermore, in case of warehouse picking performed over a wide area, the travel time component becomes predominant (Tompkins *et al.*, 2010), making the benefits observable in the net picking time t^j_{net} potentially irrelevant.

Then, in Equation (1) the error unitary cost c^j_E, considering the different errors introduced in Table I and the operator hourly cost $c_{h,p}$, can be expressed as:

$$c^j_E = c_{h,P} \cdot \sum_{i=1}^{4} p^j_{e_i} \cdot t^j_{e_i} \tag{6}$$

where p_{e_i} is the occurrence probability for each kind of error e_1, e_2, e_3, e_4, expressed as a percentage, and t_{e_i} is the corresponding time, both of which vary according to the considered technology (Figure 1 and Table III).

Table IV reports some of the possible main cost items for each of the considered paperless picking systems. The costs related to the number of stock locations generally consist of two main components: the cost of purchase of the required specific equipment and the cost of installation of such materials. The picker costs relate to the devices supplied to the picker and the hourly pay. Finally, for all the technologies the reported fixed costs concern the purchase of the management server and of the software.

4. Application to real case studies

This section reports on some case studies with the aim of presenting an example of the application of the model in order to better show the correlation of the different factors, the points on which it would be interesting to focus and their consequent impact on the hourly cost function. Such functions were plotted for all the analysed paperless picking

Table III. Paperless picking technologies time factors per error type

	$t^j_{e_1}$	$t^j_{e_2}$	$t^j_{e_3}$	$t^j_{e_4}$
Barcodes handheld	t^j_c	$2 \cdot t^j_{net}$	$2 \cdot t^j_{net} + t_{trav}$	t^j_{tot}
RFID tags handheld	t^j_c	$2 \cdot t^j_{net}$	$2 \cdot t^j_{net} + t_{trav}$	t^j_{tot}
Voice picking	t^j_c	$2 \cdot t^j_{net}$	$2 \cdot t^j_{net} + t_{trav}$	t^j_{tot}
Traditional pick-to-light	–	–	$2 \cdot t^j_{net} + t_{trav}$	t^j_{tot}
RFID pick-to-light	–	$2 \cdot \left(t^j_{net} - t^j_c\right)$	–	t^j_{tot}

	c_{SL}^{j}	$c_{d,P}^{j}$	c_{F}^{j}
Barcodes handheld	Barcode cost Barcode installation cost	Barcode reader handheld cost Picker cart cost	Server and software cost
RFID tags handheld	Tags cost Tags installation cost	RFID tag reader handheld cost Picker cart cost	Server and software cost
Voice picking	Barcode cost Barcode installation cost	Headset and microphone cost Picker cart cost	Server and software cost
Traditional pick-to-light	Lights cost Confirmation device cost Lights and/or confirmation device installation cost	Handheld cost Picker cart cost	Server and software cost
RFID pick-to-light	Tags cost Lights cost Tags and lights installation cost	RFID glove Picker cart cost	Server and software cost

Table IV. Paperless picking technologies main cost items

technologies for two different proposed warehouse configurations, which have both been derived from the simplification of two different case studies. The first case study concerns a low-level picking warehouse using voice picking technology, with a proposed configuration composed of 20 shelving units, 100 metres long with 100 stock locations each; therefore, with a total number of stock locations n_{SL} equal to 2,000. The second configuration consists of multilevel picking shelving (dimensions 3 m × 1.5 m) with a total of 50 stock locations (average dimensions 0.3 m × 0.3 m); this refers to a real case study in which a traditional pick-to-light system was adopted. The data for the two case studies have been used to set up the first two cost configurations, on the basis of which some parametric analyses are proposed.

Both warehouse layouts affect in different ways some of the components of the picking time, in terms of net picking time and travel time. In particular, in the case of the second warehouse configuration (picking from single shelving) the time needed to search for the item and to pick and to store it in the cart were observed to be slightly lower than in the first configuration, due to the fact that in this case the operator can more identify easily the products to pick and can store the picked items in a faster way since he or she does not need to move from the initial position. Furthermore, the considerations made for this configuration are even more interesting because the net picking time t_{net} is very close to the total picking time t_{tot} (due to absence of time spent in travelling and getting on and off of the picking cart, t_{trav}).

In order to perform the analysis of the existing systems and their comparison with the other different paperless picking technologies, the corresponding times and the error percentages have been calculated or estimated through observations carried out in the field at the two warehouses (for the barcode handhelds, the voice picking system and the traditional pick-to-light system) and some laboratory tests (for the RFID tags handhelds and the RFID pick-to-light system), which in some cases have also been integrated with the data obtained for the other solutions and with assumptions derived from the authors' experience. Table V presents the information time, search time, actual pick time, confirm time and consequent net picking time obtained for each paperless picking technology, together with the average travel time t_{trav} and the consequent total picking time t_{tot}. For the estimation of the actual pick time and

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of the store time, the product to pick that was considered is a normal carton box, which is easily graspable and accessible, and picked one at a time ($n=1$). In the case of $n_{SL}=2{,}000$, the considered box is 20 cm^3 and 400 g, while in the case of $n_{SL}=50$ the average dimensions are 10 cm^3 and 200 g. Consistent with what is represented in Figure 1, the search time t_s is equal to 0 for the two pick-to-light solutions since the operator gets the information about the product to pick and at the same time sees where it is located; furthermore, the confirm time t_c is not present for the voice picking system and for the RFID pick-to-light system: in the first case the confirm activity is done by the operator during the storing of the product on the cart, while in the second the picking confirmation is performed automatically by the RFID glove during the physical pick, without any further activity required from the picker.

Table VI shows the error percentages for the four different kinds of error: the values for the detectable errors 1 and 2 have been estimated by interviewing the warehouse managers, while the propagating error percentages have been calculated from the analysis of sample data collected from the picking tours performed in one month. These calculated data have then been extended to all the studied paperless systems. Finally, Table VII reports the various cost components obtained from specific industry catalogues and from information derived from the warehouse managers interviews. For the calculation of h_{SL}, $h_{d,P}$ and h_F two years were considered, with an eight-hour work shift for 220 days a year. It is important to underline that obtaining and handling all the input data is a fundamental phase that can require a great effort for people to take part in the field analysis or manager interviews; however, a parametrical analysis

Table V. Net picking time and respective time components, travel time and total time for the analysed paperless picking solutions

		t_i^j (s)	t_s^j (s)	t_p^j (s)	t_c^j (s)	t_{net}^j (s)	t_{trav} (s)	t_{tot}^j (s)
Barcodes handheld	$n_{SL}=2{,}000$	2.98	7.96	4.87	4.02	19.83	120.00	139.83
	$n_{SL}=50$	2.98	2.05	2.53	4.02	11.58	20.00	31.58
RFID tags handheld	$n_{SL}=2{,}000$	2.98	7.96	4.87	2.48	18.29	120.00	138.29
	$n_{SL}=50$	2.98	2.05	2.53	2.48	10.04	20.00	30.04
Voice picking	$n_{SL}=2{,}000$	4.85	8.12	2.97	0.00	15.94	120.00	135.94
	$n_{SL}=50$	4.85	2.00	1.99	0.00	8.84	20.00	28.84
Traditional pick-to-light	$n_{SL}=2{,}000$	4.85	0.00	2.86	0.98	8.69	120.00	128.69
	$n_{SL}=50$	2.16	0.00	1.54	0.98	4.68	20.00	24.68
RFID pick-to-light	$n_{SL}=2{,}000$	4.85	0.00	2.86	0.00	7.71	120.00	127.71
	$n_{SL}=50$	2.16	0.00	1.54	0.00	3.70	20.00	23.70

Table VI. Error picking time factors and corresponding occurrence probability for the analysed paperless picking solutions

		$t_{e_1}^j$ (s)	$p_{e_1}^j$ (%)	$t_{e_2}^j$ (s)	$p_{e_2}^j$ (%)	$t_{e_3}^j$ (s)	$p_{e_3}^j$ (%)	$t_{e_4}^j$ (s)	$p_{e_4}^j$ (%)
Barcodes handheld	$n_{SL}=2{,}000$	4.02	4.5	39.66	4.5	159.66	4.5	139.83	5.0
	$n_{SL}=50$	4.02	4.5	23.16	4.5	43.16	4.5	31.58	5.0
RFID tags handheld	$n_{SL}=2{,}000$	2.48	4.5	36.58	4.5	156.58	4.5	138.29	5.0
	$n_{SL}=50$	2.48	4.5	20.08	4.5	40.08	4.5	30.04	5.0
Voice picking	$n_{SL}=2{,}000$	1.00	4.5	31.88	4.5	151.88	4.5	135.94	5.0
	$n_{SL}=50$	1.00	4.5	17.68	4.5	37.68	4.5	28.84	5.0
Traditional pick-to-light	$n_{SL}=2{,}000$	–	–	–	–	137.38	2.0	128.69	5.0
	$n_{SL}=50$	–	–	–	–	29.36	2.0	24.68	5.0
RFID pick-to-light	$n_{SL}=2{,}000$	–	–	15.42	1.0	–	–	127.71	5.0
	$n_{SL}=50$	–	–	7.40	1.0	–	–	23.70	5.0

Cost component	Factor		Barcodes handheld	RFID tags handheld	Voice picking	Traditional pick-to-light	RFID pick-to-light
$C^j_{h,SL} = \frac{n_{SL} \cdot c^j_{SL}}{h_{SL}}$	c^j_{SL}		1.10 €	1.30 €	1.10 €	50 €	22.30 €
	n_{SL}		2,000 or	2,000 or 50	2,000 or 50	2,000 or 50	2,000 or 50
	h_{SL}		50	3,520 h	3,520 h	3,520 h	3,520 h
			3,520 h				
$C^j_{h,P} = \left(c_{h,P} + \frac{c^j_{d,P}}{h_{d,P}}\right) \cdot \left\lceil \frac{n_R}{\dot{p}^j} \right\rceil$	$c_{h,p}$	$n_{SL} = 2{,}000$	30 €/h	30 €/h	30 €/h	30 €/h	30 €/h
	$c^j_{d,P}$	$n_{SL} = 50$	2,800 €	2,900 €	3,000 €	2,800 €	2,600 €
	$h_{d,p}$		3,520 h	3,520 h	3,520 h	3,520 h	3,520 h
	$\dot{p}^j$		25.75 r/h	26.03 r/h	26.48 r/h	27.97 r/h	28.19 r/h
			114.00 r/h	119.84 r/h	124.83 r/h	145.87 r/h	151.90 r/h
$C^j_{h,E} = c^j_E \cdot n_R$	c^j_E	$n_{SL} = 2{,}000$	0.135 €	0.131 €	0.126 €	0.077 €	0.054 €
		$n_{SL} = 50$	0.040 €	0.036 €	0.033 €	0.015 €	0.010 €
$C^j_{h,F} = \frac{c^j_F}{h_F}$	c^j_F		30,000 €	30,000 €	30,000 €	30,000 €	30,000 €
	h_F		3,520 h	3,520 h	3,520 h	3,520 h	3,520 h

Table VII.
Cost components values for the analysed paperless picking solutions

of the output data can also be performed to enable the impact of the choice of values to be understood.

In the following, the first parameter that has been varied in the plotting of the hourly cost function for the two proposed warehouse configurations is the number of picked rows n_R (Figures 2 and 3): besides the line charts of the different solutions, in the lower part a bar graph is shown, reporting the areas of convenience for the various systems; that is, the most convenient system, according to the different numbers of requested picking rows, is each time reported. This last representation is also employed in the subsequent analysis in which two parameters, c_F and t_{trav}, have been changed with respect to the starting configurations, called 2a in the case of $n_{SL} = 2{,}000$ and 2b for $n_{SL} = 50$ (see Figures 4-7).

From the observation of the graphs reported for the different cost values in Figures 2 and 3, some interesting considerations and comparisons can be performed. In general, it is observed that the increase in the number of picked rows n_R leads to an increase in the trend observable for all the curves, mainly due to the increase in the number of pickers needed to satisfy the requested warehouse performance. Focusing on the different considered technologies, it is evident that, apart from the values assigned to the different cost components, a traditional pick-to-light system is more suitable for multilevel picking on single shelving ($n_{SL} = 50$), since in this case the hourly cost is lower than in a low-level picking warehouse configuration, in which the stock locations cost is absolutely impacting, making such a paperless picking solution not competitive. The case of systems relying on barcode scanner and RFID tag scanner handhelds is different: they turn out to be quite competitive for both warehouse configurations, above all for low values of n_R. The trend of the hourly cost function for voice picking is quite regular and similar to the two handhelds solutions; in the case of $n_{SL} = 2{,}000$ this solution is the most advantageous, together with those for the handheld and barcodes and the handheld and RFID tags, for $n_R < 160$ picks/h. As far as the RFID pick-to-light system is concerned, it turns out to be the most competitive for $n_{SL} = 50$ and $n_R > 10$ picks/h, since it warrants short picking times and error percentages; therefore, it can also be successfully employed for feeding picking for assembly systems (Battini *et al.*, 2013). However, for warehouse picking over a wide area ($n_{SL} = 2{,}000$) such a system becomes competitive only for higher values of n_R.

Figures 4 and 5 show the results for $n_{SL} = 2{,}000$) concerning the change of t_{trav} and c^j_F, respectively. In the first figure, the halving of the travel time leads to an increase of

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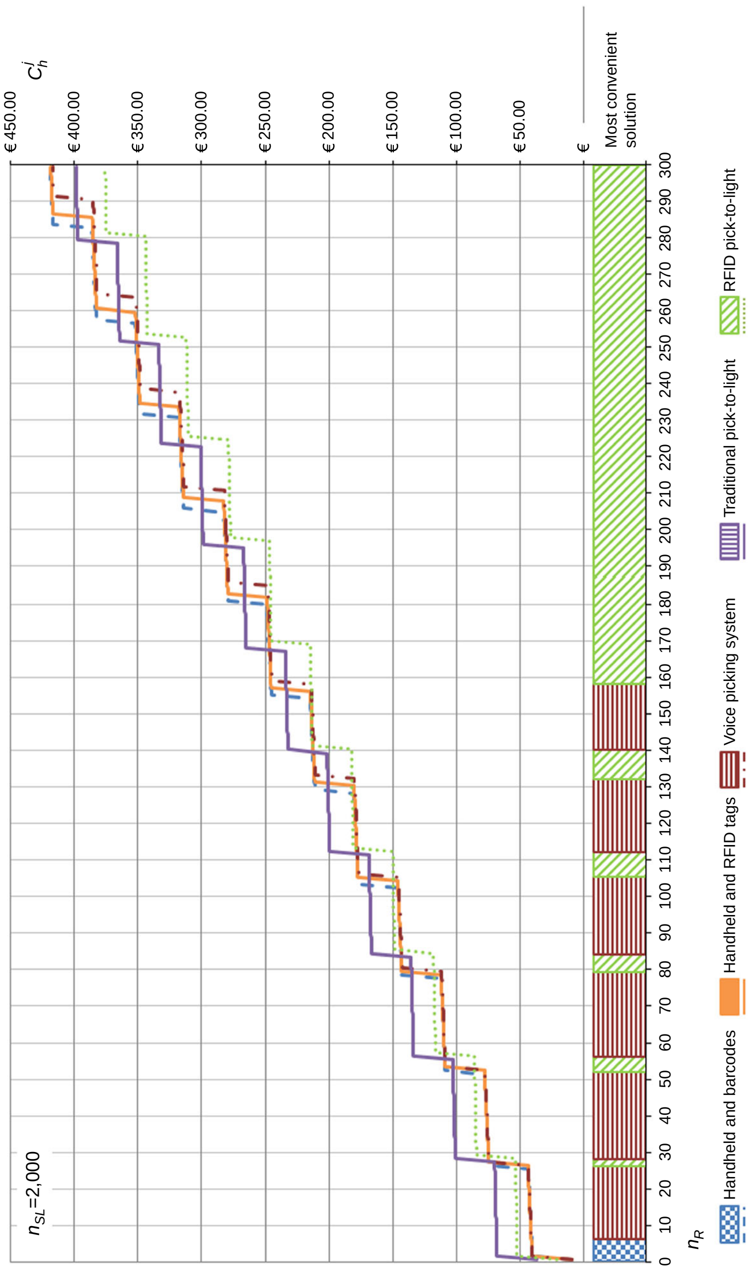

Figure 2.
Hourly cost function for the different paperless picking technologies, $n_{SL} = 2{,}000$

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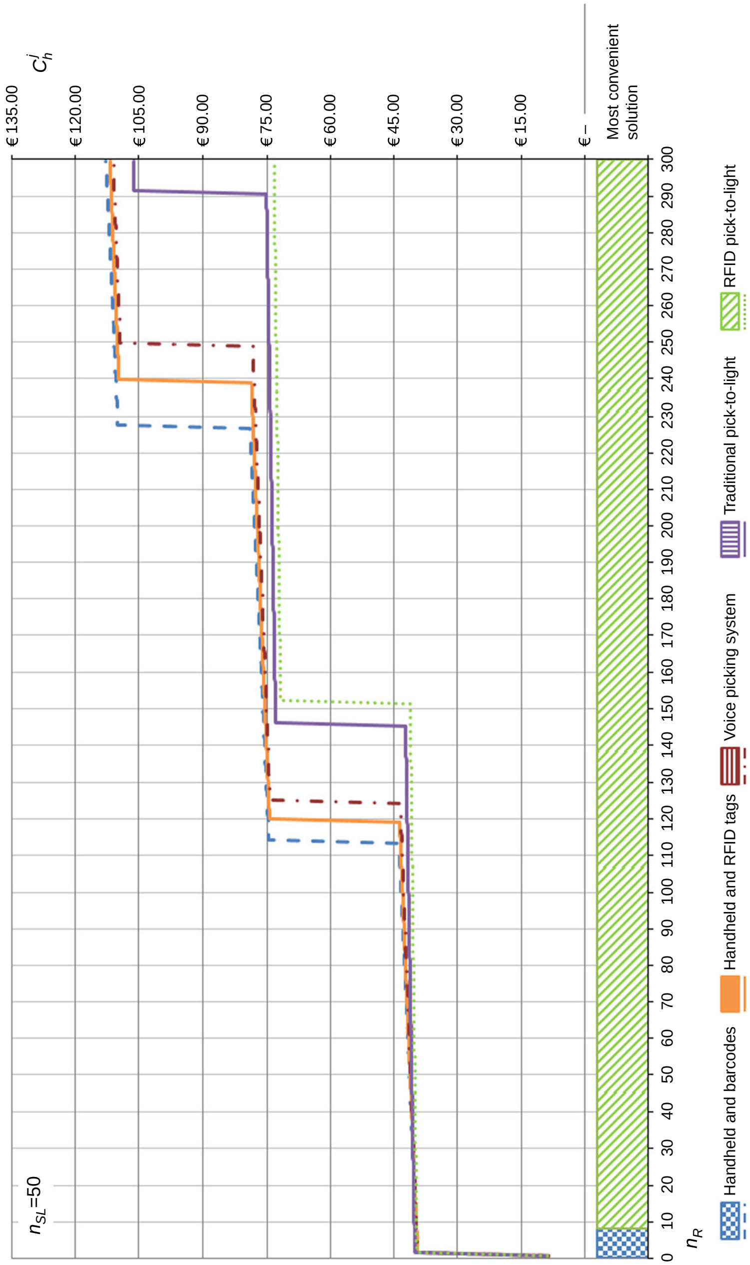

Figure 3.
Hourly cost function for the different paperless picking technologies, $n_{SL} = 50$

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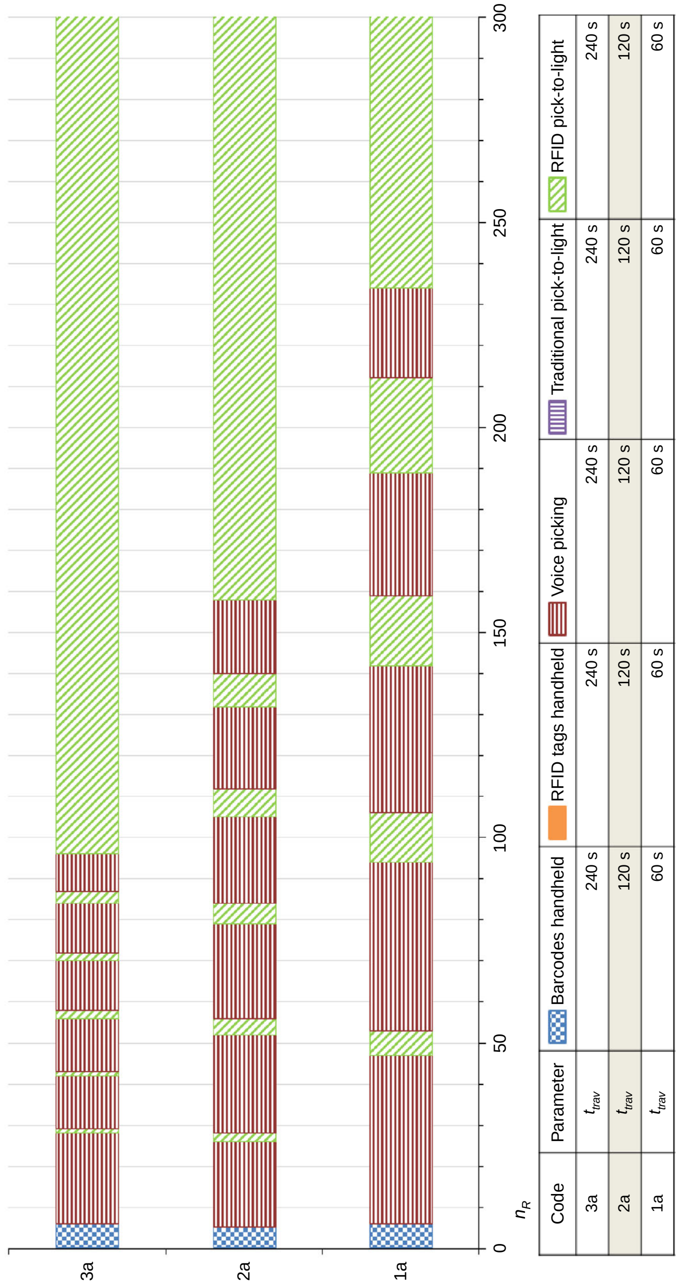

Figure 4.
Hourly cost function analysis for the different paperless picking technologies, changing t_{trav}, $n_{SL} = 2{,}000$ and $c_F^j = 30{,}000€$

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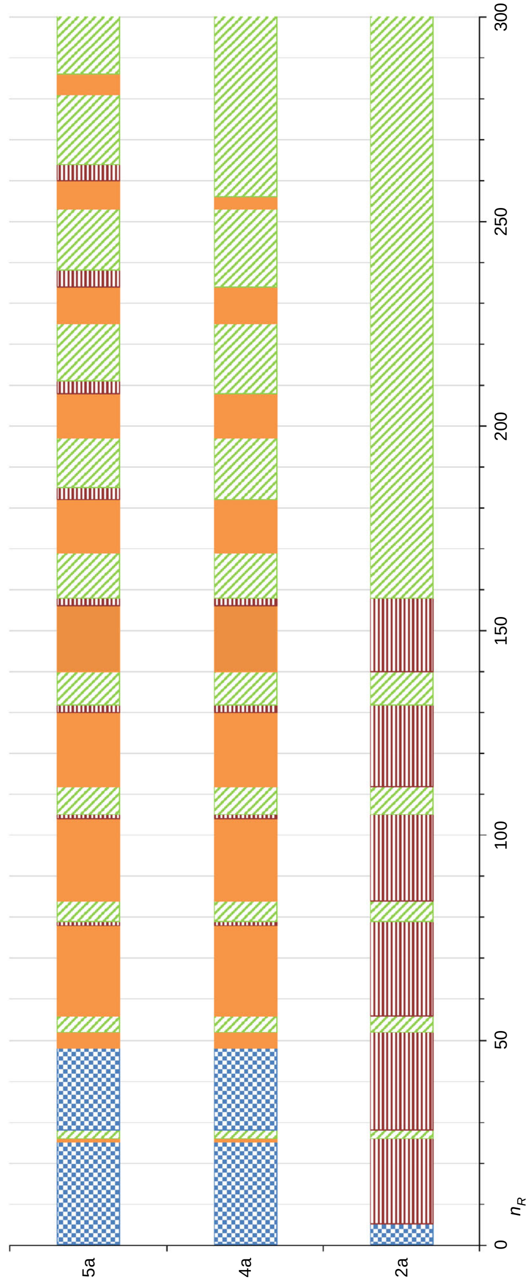

Code	Parameter	Barcodes handheld	RFID tags handheld	Voice picking	Traditional pick-to-light	RFID pick-to-light
5a	c_F	30,000€	30,000€	60,000€	90,000€	90,000€
4a	c_F	30,000€	30,000€	60,000€	60,000€	60,000€
2a	c_F	30,000€	30,000€	30,000€	30,000€	30,000€

Figure 5.
Hourly cost function analysis for the different paperless picking technologies, changing c_F^j, $n_{SL} =$ 2,000 and $t_{trav} = 120$ s

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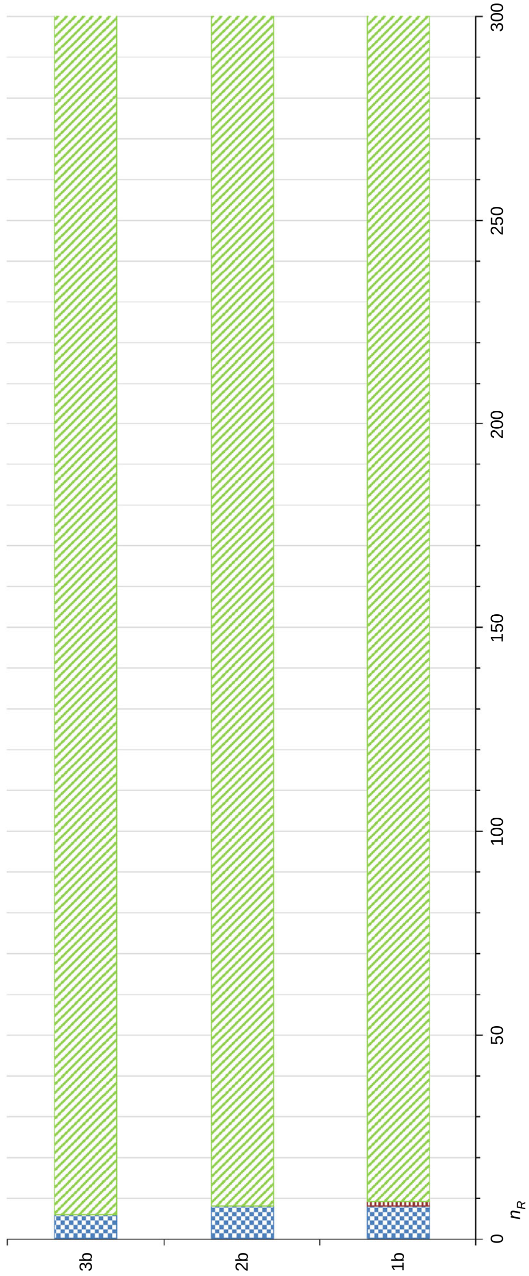
the convenience intervals for the voice picking system with respect to the RFID pick-to-light system. On the other hand, its doubling makes such intervals narrower and more concentrated on the left side of the graph, corresponding to lower values of n_R. For the analysis of the change of the fixed costs c_F^j it was decided to show a possible difference in this parameter for the various solutions, since an equal change for all the paperless picking systems would not have any effect on the convenience thresholds. Considering the voice picking system and the two pick-to-light systems that have a higher c_F^j it is noticeable that the handheld with the RFID tags becomes the more convenient solution for some intervals of n_R, instead of the voice picking system and the RFID pick-to-light system (Figure 5, code 4a). If the two pick-to-light systems have an even higher c_F^j (Figure 5, code 5a), the RFID pick-to-light convenience area decreases, while the voice picking system and the handheld with RFID tags are also suitable in the case of a higher number of picked rows per hour. A comparable trend is observable for $n_{SL} = 50$ (Figures 6 and 7), where the most convenient solutions are the handheld with barcodes for very low values of n_R, the handheld with RFID tags, the voice picking system and the RFID pick-to-light system. In particular, the increase of the travel time t_{trav} leads to a reduction of the convenience threshold of the barcode handheld (Figure 6). The introduction of different fixed costs for the various solutions makes the RFID handheld convenience intervals wider, and in case the pick-to-light solutions have a very high c_F^j, the voice picking also gains a little convenience area (Figure 7, code 5b).

5. Conclusions

Warehouse manual picking is one of the most critical activities in a warehouse: every improvement made in this area can lead to good results in terms of time and cost saving (De Koster *et al.*, 2007; Grosse *et al.*, 2015). In this sense, the development of devices able to support and help the pickers during their work, such as the paperless picking technologies, is of particular interest (Frazelle, 1988; Tolliver, 1989). The present paper has introduced a useful comparison of different paperless picking systems (i.e. handheld and barcodes, handheld and RFID tags, voice picking system, traditional pick-to-light, RFID pick-to-light), both from a technological and an economic point of view. In particular, starting from the functional description of the solutions, the different errors arising have been pointed out, which have been also taken into account in the development of the hourly cost function. In fact, the proposed cost function is composed of four main hourly cost factors: the stock locations cost, the pickers cost, the picking errors cost and the fixed cost. The cost model has then been employed in a case study concerning the comparison of the different analysed technologies in two different warehouse configurations: a low-level manual picking warehouse, composed of different racks and aisles, and multilevel picking shelving. The study outcomes show that the best paperless picking solutions for the low-level manual picking warehouse with a medium-low number of picked rows per hour are the handheld solutions (both those with barcodes and those with RFID tags) and the voice picking system, while the RFID pick-to-light solution is the best one when the number of picks per hour is high. On the contrary, in the case of the multilevel picking shelving, the most convenient technology is the RFID pick-to-light system for almost all the numbers of picked rows per hour. The proposed model represents an interesting approach which is considered useful for evaluating different paperless picking technologies, considering also their practical employment within a specific warehouse characterised by a certain layout configuration and a particular picking rate. Furthermore, its simplicity makes it easy for warehouse staff to apply directly; in any event, the engagement of warehouse



Code	Parameter	Barcodes handheld	RFID tags handheld	Voice picking	Traditional pick-to-light	RFID pick-to-light
3b	t_{trav}	40 s	40 s	40 s	40 s	40 s
2b	t_{trav}	20 s	20 s	20 s	20 s	20 s
1b	t_{trav}	10 s	10 s	10 s	10 s	10 s

Figure 6.
Hourly cost function analysis for the different paperless picking technologies, changing t_{trav}, $n_{SL} = 50$ and $c_F^j = 30,000€$

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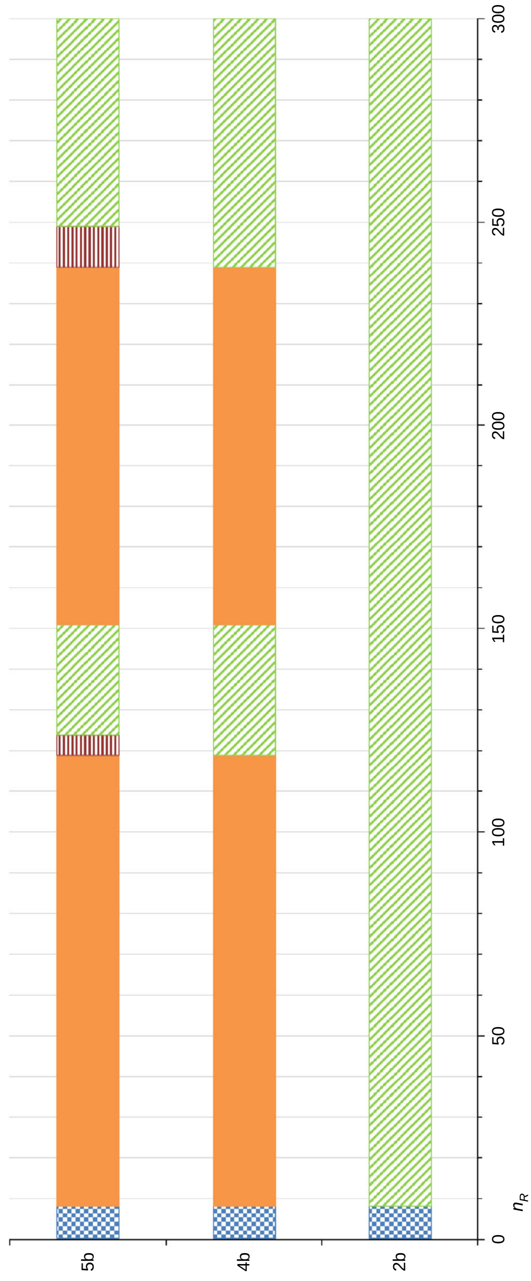

Code	Parameter	Barcodes handheld	RFID tags handheld	Voice picking	Traditional pick-to-light	RFID pick-to-light
5b	c_F	30,000 €	30,000 €	60,000 €	90,000 €	90,000 €
4b	c_F	30,000 €	30,000 €	60,000 €	60,000 €	60,000 €
2b	c_F	30,000 €	30,000 €	30,000 €	30,000 €	30,000 €

Figure 7.
Hourly cost function analysis for the different paperless picking technologies, changing c_F^j, $n_{SL} = 50$ and $t_{trav} = 20$ s

managers is certainly needed in order to obtain and eventually verify the most accurate times, errors and cost values. In fact, an important point for attention in such a method is the need for the correct estimation of the input data. Further studies in this field will be focused on the enrichment of the economic comparison by introducing other technologies, the study of other warehouse configurations and the evaluation of their applicability to the picking for the feeding of assembly systems.

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