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Railway safety by designing the layout of inland terminals with dangerous goods connected with the rail transport system

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ABSTRACT

While rail transport is growing for medium-distance journeys, the first and last miles are travelled by road, marking a change of transport mode in inland terminals (ITs). Moreover, the introduction of ITs in seaport hinterlands is increasing with a view to decongesting ports, and the best transport mode to connect these ITs with ports is that of rail.

In 2013, chemicals were involved in 48 rail accidents in the EU-28 and in 667 in the United States (US). An appropriate design for the layout of inland terminals for containers with dangerous goods (ITDGs) involved in the rail system will increase the safety and operability of rail transport, avoiding accidents such as Tianjin (2015).

The novelty of this work is a methodology to design the layout of ITDGs involved in rail transport through a hierarchy of container handling equipment (CHE), used in the yard of the terminal for a safer, more resilient and more environmentally friendly rail transport.

The AHP (analytic hierarchy process) was used to hierarchize five alternative layouts, one for each CHE used in the yard; and according to criteria belonging to three areas: safety and security, environment and equipment performance. Results show that a layout linked to platforms is the preferred alternative for storing containers with dangerous goods (DGs) in ITs connected to railways.

The implementation of this methodology will reduce consequences in the case of a serious accident in, or terrorist attack on, ITDGs involved in the rail system and GHG (greenhouse gas) emissions in the terminal.

1. Introduction

From 1995 until 2013, the transport of goods increased by 13.8% (from 3060 billion tonne-kilometres (tkm) in 1995 to 3481 billion tkm in 2013) in the EU-28, of which 406.50 billion tkm (11.7%) were transported by rail in 2013 (European Union Road Federation, 2016). In the case of the United States (US), from 2012 until 2015 the transport of goods increased by 5% (from 7098 billion tkm in 2012 to 7473 billion tkm in 2015) (United States Department of Transportation, 2017). The most remarkable increase has been in China, where freight transport from 2006 (with 8883 billion tkm) to 2015 (with 17,835 billion tkm) has doubled (National Bureau of Statistics of China, 2017). The increase in the transport of goods produces larger flows of containers that congest seaport operations (Roso et al., 2009). One approach to deal with this increase in transport flow and its associated problems is a joint seaport and hinterland perspective, where rail transport has an important role.

The development of IT, defined as inland facilities directly connected to one or more seaports, where customers can leave and/or pick up their standardized units in the same way as in a seaport and connected with different means of transport (Roso et al., 2009), could play a key role in diminishing the pressure on the inland segment of freight distribution. This will reduce traffic, risk, and associated environmental impacts in regions surrounding ports and may become a relevant element of the supply chain. This is especially true due to the high costs for companies and legal requirements involved in seaport facilities.

The mode of transport (road, barge or rail) used to access the hinterland from the seaport will depend on the distance between them, their availability, the costs and the quality of the service (e.g. transit times). The use of rail transport, from a cost perspective, is the most competitive in distant terminals (more than 300 km). However, rail has also been used for close (less than 100 km) and mid-range terminals to

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provide a faster service, and to relieve traffic jams in the surrounding areas and at the gates of the ports, with this solution being more energy-efficient and environmentally friendly (Bask et al., 2014).

ITs are widely developed in North America and Europe, and differences between them are based on logistics ownership (public or private), the situation of the market and the history of its development and technology (Rodrigue and Notteboom, 2012). Using trains instead of road transport reduces road traffic to a large extent, since one train can replace 35–100 trucks (Roso et al., 2009). The use of rail transport instead of road transport also produces a reduction in carbon emissions of 64% (an average of 62 gCO_2/tonne-km for road freight transport compared with 22 gCO_2/tonne-km for rail transport) (Cefic, 2011). Moreover, CO_2 emissions in the terminal constitute around 5% of emissions over the total rail transport; while the rail transport of 1 TEU (twenty-foot equivalent unit) between Hamburg and Prague (676 km) emits 157 kg of CO_2, the handling of this container at Prague rail terminal emits 7 kg of CO_2 (HHLA Hamburger Hafen und Logistik AG, 2017).

In the particular case of DGs, legal rules concerning safety and environmental storage requirements limit the time they can be held in ports. Moreover, chemicals make up 20% of the total rail shipments in Europe (DESTINY, 2013), and in 2013, while being transported by rail, they were involved in 48 accidents in the EU-28 (Eurostat, 2015) and in 667 accidents in the US (US Department of Transportation PHMSA, 2017). Explosive events during the storage or transportation of chemicals are rare. However, certain products such as ammonium nitrate can explode, what could have devastating consequences such as the accident in Drevja, Norway (2013) (Due-Hansen, 2017). This highlights the importance of an appropriate design for rail ITDGs in order to increase the safety and operability of rail transport. The development and implementation perspectives of ITDGs are very positive regarding the increase in the traffic of exports and imports of chemical products (UNCTAD, 2016), and all the requirements for the ports of the future: green, cost-efficient, safe and secure, resilient and socially inclusive (Zarli et al., 2016).

Given the increasing importance of ITDGs connected with the railway system, it seems necessary to tackle the design of these kinds of logistics facilities in a decision-making process involving relevant stakeholders to increase the safety and environmental care of container rail transport and to reduce the accidentability.

The objective of this manuscript is to study the design of the layout of these rail ITDGs by achieving the following specific objectives:

a. To identify stakeholders related to the decision-making process and to create an appropriate expert panel.
b. To identify criteria involved in the decision-making process and possible layout alternatives.
c. To define a methodology to hierarchize these alternatives taking into account all relevant points of view.

1.1. Design factors involved in ITDGs

The design and management of efficient container terminals using optimization methods has been increasingly studied during the last few years, especially for the case of maritime ports. These studies have been focused on: equipment performance, environmental care, and safety and security.

1.1.1. Equipment performance

Most recent papers published on the topic were focused on container handling equipment (CHE) performance in: a study of costs, an indirect approach based on the minimization of loading–unloading operating time and space optimization.

1.1.1.1. Costs. Lee and Kim (2013) proposed an optimization model to determine the layout of a container yard. The authors considered two types of yard layout when yard cranes were used as CHE. One was a parallel layout in which blocks are laid out parallel to the quay, while the other was a perpendicular layout in which blocks are laid out perpendicular to the quay. The objective was to minimize the total operational cost. When comparing the parallel layout with the perpendicular layout, it was found that the parallel layout is superior to the perpendicular layout in terms of total operational cost.

1.1.1.2. Handling time. With a similar purpose, Wiese et al. (2013) studied the best layout design when using straddle carriers as CHE in order to minimize the cycle times. The results showed that it cannot be concluded that a parallel layout is superior to a perpendicular layout. Said and El-Horbaty (2015) proposed an optimization methodology for solving container handling problems using the genetic algorithm applied to real data from a container terminal at Port Said port in Egypt. The proposed approach reduced the ship service time in the port (loading/unloading) by 56%.

Following this main idea of time saving, Meisel and Bierwirth (2013) tried to minimize the required time for loading and unloading vessels and Alessandri et al. (2008) proposed a dynamic discrete-time model of the flows of containers in maritime terminals. Guo and Huang (2012) proposed a hierarchical scheme for yard crane workload management in container terminals. The scheme combines simulation and optimization to improve the efficiency, minimizing the average vehicle job waiting time at yard side.

1.1.1.3. Space optimization. The high price of the ground surrounding seaports and the expansion difficulties have encouraged researchers to look for smart solutions to minimize the block size of the containers in relation to the different cranes used (Lee and Kim, 2013). To improve the design of the port terminals, Kang et al. (2008) developed a mathematical model that optimized the fleet size to be used in the operations involving containers unloading from the ships, bearing in mind the required space and the number of CHE units. Jin et al. (2016) studied the daily storage yard management problem, dividing it into a storage space allocation problem and a yard crane deployment problem.

1.1.2. Environmental care

Some of the recent existing papers developed mathematical models and simulations by evaluating different CHE options with the goal of diminishing the energy expense. Arango et al. (2013) proposed a mathematical model aimed at minimizing the distance covered by the equipment used in the loading and unloading operations; other research was devoted to reducing the broadcasts from the trucks in slow motion, minimizing the patterns of arrival of the trucks (Chen et al., 2013), and the problem of battery autonomy in terminals with automated guided vehicles was tackled too (Bian et al., 2015). He et al. (2015) proposed a yard crane scheduling problem with a view to energy saving. Subsequently, a simulation was designed for evaluating solutions, and exploring the solution space dealing with several kinds of CHE: quay cranes, internal trucks and yard cranes. Yang and Lin (2013) compared different kinds of CHE used in terminals based on the three performance dimensions of working efficiency, energy saving and carbon reduction performances.

1.1.3. Safety and security

We can find systematic studies about container handling from a safety point of view (Murdoch and Tozer, 2012) that consider lashing systems and the identification of weaknesses regarding proper stowage and safe working procedures. However, studies on the design of container terminals from a safety and security point of view are very scarce. Peilin et al. (2012) published a book chapter dealing with a layout evaluation index system for ports with DGs based on the analytic hierarchy process (AHP) method. And Glickman and Erkut (2007) estimated critical impact distances of six different chemicals using modeling tools.

The analysis of the state of the art concluded that among the papers dealing with the optimization of the layout of container terminals, authors establish three main areas of interest: equipment performance, environmental care and safety in a minor extent. The design of ITDGs taking into account these three areas in a simultaneous way through the CHE operating has not been carried out.

1.2. Multicriteria decision analysis

Multicriteria decision-making (MCDM) techniques like the AHP method used in this paper are useful procedures to apply when there are multiple criteria to take into account and it is necessary to prioritize them in a project management framework (Gogas et al., 2014). The different MCDM methods are based on distinct theoretical foundations such as optimization of results, achievement of an aim or goal, or a combination of these. The common purpose of the diverse techniques is being able to evaluate and choose between several alternatives on the basis of a systematic analysis.

After a literature review and analysis of advantages and disadvantages of available methods (Mulliner et al., 2016; Roy and Słowiński, 2013; Velasquez and Hester, 2013; Zanakis et al., 1998), AHP was selected to develop this study due to: (i) its ease of use, (ii) its intuitive design and scalability, (iii) its ability to simplify the problem in different criteria clusters, resulting in a hierarchy that allows a better understanding of the problem, and (iv) its systematic and traceable method to calculate criteria weights and evaluate the alternatives. However, some disadvantages of AHP are its susceptibility to rank reversal and interdependence between criteria and alternatives (Roy and Słowiński, 2013; Velasquez and Hester, 2013). To solve this, the result robustness needs to be analysed by calculation of consistency ratios and sensitivity analysis.

In addition, the bibliometric study developed by Tramarico et al. (2015) for MCDM methods applied to the supply chain, in which railway terminals are included, revealed that the multicriteria method most used in publications from 2011 to 2014 is the AHP, making it therefore the appropriate method for this type of study.

In the AHP method (Saaty, 1980, 2013, 2016) criteria prioritization is done by an expert panel where the different stakeholders are involved. Cascetta et al. (2015) defined stakeholders involved in the transport field as "people and organizations who hold a stake in a particular issue, even though they have no formal role in the decision-making process". It is possible to find in the literature a considerable growth in the applications of the AHP method to decision-making procedures related to infrastructure engineering, and some of them applied to rail transport (Aragonés-Beltrán et al., 2014; Hasan et al., 2012; Montesinos-Valera et al., 2017) and sustainable manufacturing (Harik et al., 2015).

Recently, the application of the method was related to the comparison of different logistic facilities. As an example, Yang (2015) used AHP to determine the degree of importance of green container terminal assessment criteria in order to identify the ranking order of six main commercial ports in the Far East area.

Kayikci (2010) used a combination of fuzzy-AHP and artificial neural network methods to select the best location for an intermodal freight logistics centre within given selection alternatives. Golbabaie et al. (2012) applied AHP to compare three layout configurations of a terminal based on their productivity. Costs, flexibility, transfer cycles and storage capacity were the criteria considered, but environmental and safety factors were not taken into account. Jahromi et al. (2012) applied the AHP method for selecting between vertical and horizontal stacking layout types regarding three criteria: management, operational area and operational time.

It is necessary to broaden the existing literature to cover the growing requirements of the global market regarding DGs. In this field, environmental care, safety and security considerations are unavoidable, due to the inherent characteristics of these products, when designing the layout of rail ITDGs.

In the present paper, the rail ITDGs layout design is studied by means of the prioritization of CHE alternatives used in the yard, due to the univocal relationship between CHE and the layout design (Monfort Mulinas et al., 2011). We used the AHP in our research due to its successful application in several knowledge areas (Tramarico et al., 2015) and its suitability for the case being analysed. Application of AHP contributes to the design of ITDGs with a structured and novel analysis that allows establishing a hierarchy of alternatives and weighing them based on a scientifically contrasted procedure which considers three different study areas in the hierarchical model. Therefore, while a cost benefit analysis only allows comparison between different alternatives for cost and benefit criteria, AHP allows holistic evaluation of alternatives, considering both quantifiable criteria (e.g. costs), and non-quantifiable criteria (e.g. emergency procedures or the automation level of the equipment).

2. Methodology

The planned methodology is based on use of the AHP multidecision-making method for the prioritization of different yard layout alternatives given different criteria, obtained from a previous work (Molero et al., 2016; Molero Prieto, 2016). This study also used AHP to obtain criteria weights for the design of container terminals with dangerous goods, taking into account five areas of criteria: safety and security, environmental care, equipment performance, information and communication technologies, and business intelligence. Since this work is focused on three of these criteria: safety and security, environmental care, and equipment performance, criteria weights have been normalized from five to three areas, for use in the AHP model. Criteria and their global normalized weights (W_{CG_k}) can be seen in Appendix Table 1.

After identifying criteria and obtaining weights, possible alternatives for goal achievement are evaluated taking into consideration all weighted criteria to prioritize them. Thus, criteria and alternatives are elements of decision in the problem that build up the hierarchy model together with the goal.

The working scheme followed in this manuscript is detailed hereafter:

(a) The expert panel was constituted.
(b) Criteria were explained to the members of the expert panel.
(c) The working team established layout alternatives in relation to the used CHE and defined the hierarchical model in order to apply the AHP.
(d) The expert board completed surveys that resulted in alternative matrices of comparison. In these matrices, comparisons were made between alternatives for each criterion, and alternative prioritization was obtained using the mathematical software "Super Decisions".
(e) Finally, we evaluated the robustness of the method by carrying out a sensitivity analysis, which is a valuable method to evaluate rank reversal, a known drawback of AHP.

2.1. Expertise panel definition

The expert panel used to identify all possible CHE or layout alternatives and to judge them from the perspective of each criterion was created taking into consideration: (i) stakeholder theory (Reynolds et al., 2006), to avoid conflicts of interest, and (ii) stakeholder management principles (Clarkson Centre for business ethics, 1999). It comprised:

1. A centre of technology (AITEC) working on the development of innovative processes in the area of safety and environment regarding

DG logistic processes, represented by two expert technicians.

2. Sustainable development institute (IMEDES-Mediterranean Institute for Sustainable Development), represented by the head managing director and a technician.
3. Automatism and information and communication technology company (JOFESA), represented by the head manager and a senior engineer. These experts have wide experience in the control of network systems on a large scale, automatism, machinery, and wireless sensor and robotic solution networks; and participated in the definition and analysis linked to equipment of rail ITDGs.
4. A logistics operator company specialized in the transport of chemicals and plant-protection products and the owner of an IT devoted to containers of DGs (FITOTRANS), represented by the head manager and the QHSE (quality, health, safety and environment) coordinator. This company has expertise in equipment operating in terminals.
5. Port Institute for Studies and Cooperation (FEPORTS), represented by the research project manager and an engineer. Among their strategic lines we can find the improvement of port system effectiveness in the Valencia region, boosting policies on transport and logistics, and strengthening connections with other European and peripheral regions. This institute assumed an equipment expertise role.

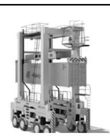
Each of these experienced professionals provided independently completed questionnaires. Consensus was achieved through the use of DELPHI methodology (Linstone and Turoff, 1975).

2.2. Layout alternatives

For the design of the layout in rail ITDGs we consider five different alternatives according to the kind of CHE to be used in this kind of facility (Lee and Kim, 2013), inasmuch as CHE defines the configuration of a container terminal (Monfort Mulinas et al., 2011).

We considered one kind of CHE operating in the terminal yard and five possible design alternatives for the yard layout (Koppe and Brinkmann, 2008; Santarremigia et al., 2017) (Table 1), in relation to the corresponding yard equipment.

Table 1
Alternatives for yard layout design based on type of CHE.

Alternative code	Yard equipment alternative		Typical layout	
			TEUs per row	TEUs per column
A1	Straddle Carrier		1	3
A2	Forklift		2	3
A3	Reach stacker		3	3
A4	Platform		1	1
A5	Gantry crane		8	5

CHE alternatives and their corresponding yard layout are:

A1. Straddle carriers: are vehicles used for lifting, moving and stacking standard containers, carrying the container between their four legs. They can stack up to three containers and in only one row of containers. The containers considered are 20-foot equivalent unit (TEU) containers. Between the batteries, a corridor from 1.2 to 2.0 m is required, and in the transversal extremes of the rows, it is necessary to leave another corridor of at least 10 m to allow the proper movement of the straddle carrier. Straddle carriers can act as equipment to carry the container out between the yard and the gates of the terminal (interconnection equipment).

A2. Forklifts: are vehicles used to move and stack containers for short distances using two forks and a carriage hydraulic system. When forklifts are used, it is possible to make rows of up to two containers of width and five to seven containers in height. Between each volume of batteries of containers, it is necessary to leave a distance of at least 10 m to allow for the manoeuvring of the forklift. Forklifts can also act as interconnection equipment.

A3. Reach stackers: have an arm that catches the container and moves it through short distances very quickly. These vehicles can be used for yard storage purposes and for the transfer of containers between modes of transport. Compared with forklifts, reach stackers have a higher load capacity, better accessibility to stacked containers, higher stability and more versatility. Reach stackers have a yard configuration of three to four TEUs in width and heights of five to seven TEUs, just like in the case of forklifts. Between batteries of containers it is necessary to leave a distance of at least 10 m. Reach stackers act as interconnection equipment.

A4. Platform/flatbed trailers: are trailers specially designed to transport the container in the terminal. Platforms do not allow the stacking of TEUs; therefore, they give place to rows of one container in width and one container in height. Furthermore, as many platforms as containers stored in the yard are needed. This alternative does not act as interconnection equipment, because the external trucks perform this function.

A5. Gantry cranes: also called portal cranes, are specialized cranes that move the containers parallel to the track over the container stacks that they have formed between their legs. This system has a high stacking capacity. Characteristic gantry crane layouts store an average of eight containers by row with heights of five containers. The width of the corridors between batteries of container blocks should be at least 5 m. This equipment does not need yard interconnection facilities either.

2.3. Hierarchical model

The alternatives, together with the three levels of criteria and the main goal, constitute the hierarchical model to apply the AHP (Fig. 1).

2.4. Prioritization process of alternatives

The opinions of the constituted expertise board are available by means of questionnaires filled in by the experts. The collected opinions constitute matrices of comparison using the scale of Saaty (1980). When a skilled expert compares two alternatives, the relative importance of one particular alternative in front of the other is provided. In terms of the preference of the element shown in a row of the matrix regarding the element shown in a column, a numeric value is given to the corresponding element of the matrix. The scale used to fill the comparison matrices is:

1. Similar. Both elements are equally preferred.
3. Moderate. One element is slightly preferred in front of the other.
5. Strong. One element is strongly preferred in front of the other.
7. Very strong. One element is very strongly preferred when compared with the other.

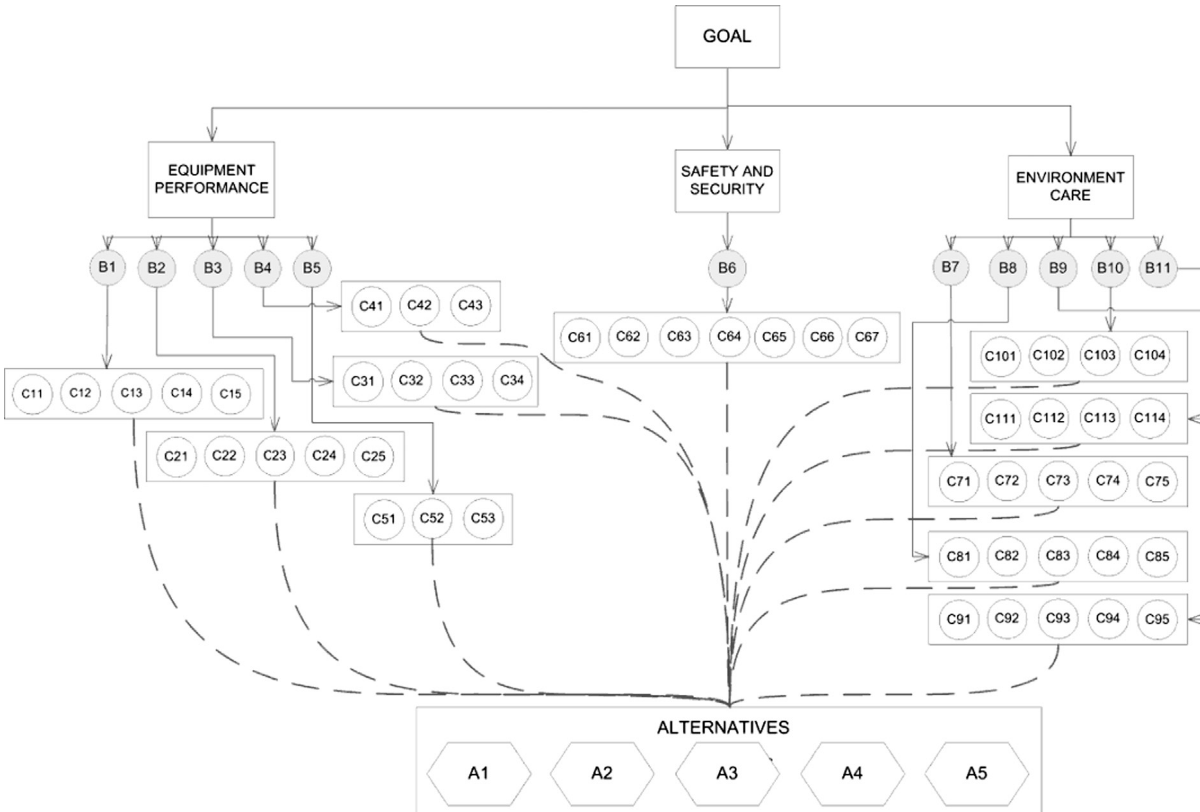


Fig. 1. Hierarchical model proposed.

9. Extreme. An element is fully preferred when compared with the other.

If, on the other hand, the expert prefers the criterion situated in the column, the value to assign would be the reverse of that previously indicated (1/3, 1/5, 1/7 and 1/9). Furthermore, experts may use intermediate values such as 2, 4, 6 or 8 if they need to refine their preferences (or 1/2, 1/4, 1/6 and 1/8) (Saaty, 2006).

To prioritize alternatives, the expert panel compared them in pairs for each of the identified criterion. The expert board completed questionnaires in private following the Delphi method (Linstone and Turoff, 1975). The Delphi method is a group structuring method aimed at reaching consensus. After filling in the questionnaires, the answers of the different experts are compared, and where there is a divergence of opinions, a second questionnaire is prepared showing the answers of the first questionnaire and the experts are asked to complete it again taking into consideration the other opinions and reconsidering their answers. This process was repeated several times till achieve a consensus. Further sensitivity analyses supposing minor changes in the judgments of the experts were also carried out (Al-Harbi, 2001).

The data collected constituted matrices of comparison as shown in Table 2. As an example, Table 2 shows the resultant matrix for comparison of five layout alternatives taking into account the preference of experts for the third level criterion personnel cost (C13) of the area equipment performance. When the expert compares two alternatives, a higher value is given to the alternative that has a lower personnel cost. Therefore, the higher the value of $w_{a_{tk}}$, the lower the personnel cost and the better alternative compared with the others. As these costs depend on the specific case, the best way to compare alternatives is using MCDM methods, such as AHP, to obtain preferences of those responsible for making decisions in container terminals.

Table 2
Comparison of the alternatives A1 – straddle carrier, A2 – forklift, A3 – reach stacker, A4 – platform and A5 – gantry crane for criterion personnel costs (C13) for the area equipment performance.

Personnel Cost (C13)	A1	A2	A3	A4	A5	$w_{a_{tk}}$
A1	1	1/3	1/3	1/5	3	0.0862
A2		1	1	1/3	5	0.2010
A3			1	1/3	5	0.2010
A4				1	7	0.4691
A5					1	0.0427

AHP allows normalized local weights of alternatives to be calculated when compared with the third level criteria ($w_{a_{tk}}$) from the expert panel survey data.

For calculation of normalized local weights ($w_{a_{tk}}$) of alternative "t" against criterion "k", the following procedure was used:

1. The n alternatives are compared in pairs for each third level criterion using Saaty's scale. These values form a comparison matrix A:

$$A = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & 1 \end{bmatrix}, \text{ where } a_{ji} = 1/a_{ij} \quad i,j = 1,\dots,n \tag{1}$$

2. The consistency ratio (CR) (Eq. (2)) of matrix A (Saaty, 2016, 2013, 1980) is used to check inconsistencies

$$CR = \frac{(\lambda_{max} - n)/(n-1)}{RI} \tag{2}$$

where λ_{max} is the larger or principal eigenvalue of matrix A, n is the size of the matrix and RI is the Random Index, which is an experimental value that depends on n (see Table 3) (Saaty and Ozdemir, 2003). Matrices with a CR of above 0.1 were rejected (Saaty, 1987).

3. The local normalized weight of all alternatives for a third level

Table 3
Random index (RI) values (Saaty and Ozdemir, 2003).

n	2	3	4	5	6	7	8
RI	0	0.52	0.89	1.11	1.25	1.35	1.40

criterion k $(w_{a_{1k}}, w_{a_{2k}}, \cdots, w_{a_{tk}}, \cdots, w_{a_{5k}})$ is the principal eigenvector of the pairwise comparisons matrix A, which is calculated by raising this matrix to a sufficiently large power:

$$q_{tl}^{z} = \lim_{z \to \infty} A^{z} \quad (3)$$

Then summing over the rows and normalizing, we obtain the local normalized weight in the zth power:

$$w_{a_{tk}}^{z} = \frac{\sum_{l=1}^{n} q_{tl}^{z}}{\sum_{t=1}^{n} \sum_{l=1}^{n} q_{tl}^{z}} \quad (4)$$

The process was stopped when the difference between $w_{a_{tk}}^{z}$ obtained at the zth power and $w_{a_{tk}}^{z+1}$ obtained at the (z + 1)th power was less than 10^{-4}.

Moreover, it is especially relevant to obtain a value of the global normalized weight for each alternative versus the main goal that allows the issue to be addressed in a holistic way ($W_{A_{tG}}$) was calculated as follows (Eq. (5)):

$$W_{A_{tG}} = \sum_{i=1}^{3} \left[\sum_{j=1}^{n_i} \left(\sum_{k=1}^{m_{ij}} (w_{ck} \cdot w_{a_{tk}}) \cdot w_{cj} \right) \cdot w_{ci} \right] = \sum_{i=1}^{3} \sum_{j=1}^{n_i} \sum_{k=1}^{m_{ij}} w_{a_{tk}} \cdot W_{CGk} \quad (5)$$

$$W_{CG_k} = w_{ci} \cdot w_{cj} \cdot w_{ck} \quad (6)$$

where w_{ck}, w_{cj}, and w_{ci} are the local normalized weights for each criterion of third, second, and first level, respectively.

Weights of each alternative in relation to the first level ($w_{a_{ti}}$) and the second level ($w_{a_{tj}}$) criteria can be calculated as follows (Eqs. (7) and (8), respectively):

$$w_{a_{ti}} = \sum_{j=1}^{n_i} \left(\sum_{k=1}^{m_{ij}} (w_{ck} \cdot w_{a_{tk}}) \cdot w_{cj} \right) \quad (7)$$

$$w_{a_{tj}} = \sum_{k=1}^{m_{ij}} (w_{ck} \cdot w_{a_{tk}}) \quad (8)$$

where

$n_i = [5,1,5]$; $m_{1j} = [5,5,4,3,3]$; $m_{2j} = [7]$; $m_{3j} = [5,5,5,4,4]$.

3. Results and discussion

3.1. Hierarchy of alternatives

$W_{A_{tG}}$ allowed comparison of the different alternatives for achieving the main goal, considering all criteria with their relative importance in a holistic process (Fig. 2A).

While studying $w_{a_{tk}}$ results (Appendix Table 2) it was pointed out that, for all third level criteria for the equipment performance area, the use of platforms (A4) is preferential ahead of other CHE, except for the cost of the floor criterion (C12), inasmuch as platforms require greater surfaces to be used in a terminal yard. Anyway, the higher surface requirements are somehow inherent to DG storage because segregation is required and TEU stacking is not recommended. Furthermore, a platform is perceived as reliable CHE in terms of environmental care, safety and security according to its $w_{a_{ti}}$ and its $W_{A_{tG}}$ values (Fig. 2). This is to be expected due to the fact that a platform does not generate excessive waste or exhibit excessive consumption, and it does not generate big direct or indirect emissions. Moreover, for a terminal of containers with dangerous substances, the use of platforms as a storage and disposal system for the terminal ensures there is no accumulation of high risks in small surface areas. Even bearing in mind the higher surface-demanding characteristic of platforms, they are considered the most inexpensive device to be used in terms of automation cost (C11), personnel cost (C13), technical maintenance cost (C14) and expansion-related cost (C15).

This result may seem surprising since platforms are not widely used in Europe in inland terminals involved in the railway transport system, perhaps for two main reasons fundamentally. On the one hand, the criterion related to the cost of the industrial floor traditionally had a high impact on decision-makers because most current ITs can be found relatively near to the port terminals. On the other hand, as the study of the state of the art revealed, the research applied to rail ITDGs seems to be partial and still under development, because papers dealing with a holistic approach to the problem are missed. So, public or private investors cannot enlist technological scientific knowledge that allows them a change to their traditional performances. However, in the United States of America the system of platforms has been widely used for a long time, both in seaports and ITs.

The second preferred yard layout alternative is related to gantry cranes (A5), which are 30% below the preferred option. We conclude from this, in accordance with the expert panel, that if the option that requires a lower level of investment and lower level of technology is not possible, the option that better satisfies the cost of the floor criteria is preferred. This second option would generate greater battery volumes at the expense of an increase in the risk of potential incidents related to safety and security and environmental care areas. Therefore, the AHP method yielded another apparently surprising result because the gantry crane option is preferred over platforms based on the floor surface needed to dispose of the containers. This is mainly due to the high degree of influence of the criterion cost of the floor (C12). So, when there is an alternative that is significantly better for all the other criteria (i.e. platforms), despite being the worst for the criterion cost of the floor, it becomes the preferred alternative. But if this alternative, which is significantly better for all other criteria, is removed, i.e. platforms cannot be used, there is not another better alternative for most criteria, and the expert panel prefers those alternatives for which the floor cost is optimized, as it is the preferred alternative in the case of gantry cranes. Nowadays, this second option of gantry cranes is used in ITs that have a high capacity for investment, generally public rail ITs.

In third and fourth position, with weights of 55% and 52%, respectively, ahead of the preferred layout alternative, come forklift (A2) and straddle carrier (A1). Both contribute to a commitment solution because they achieve intermediate satisfaction in terms of floor surface requirements and the risks associated with the environmental care and safety and security areas. These are the options mainly used at the ITs of small and average size in Spain and Europe. Finally, the reach stacker option is last in the order of preference owing to the risks associated with stacking DGs without achieving an efficient optimization of the surface.

3.2. Sensitivity analysis

The sensitivity analysis is performed by analysing (Ishizaka and Labib, 2011):

i. Variations in alternative ranking when weights of first level criteria are slightly modified.
ii. Variations in alternative ranking when weights of more influential criteria (those weighting 80%) are slightly modified.

We thought that weight modifications higher than 10% for the criteria would require reconsideration of the whole process, and it would not constitute a proper sensitivity analysis. The results obtained were quite similar to those achieved originally according to the expertise board opinions. As an example, we show the results of the sensitivity analysis when varying w_{ci} value for the equipment

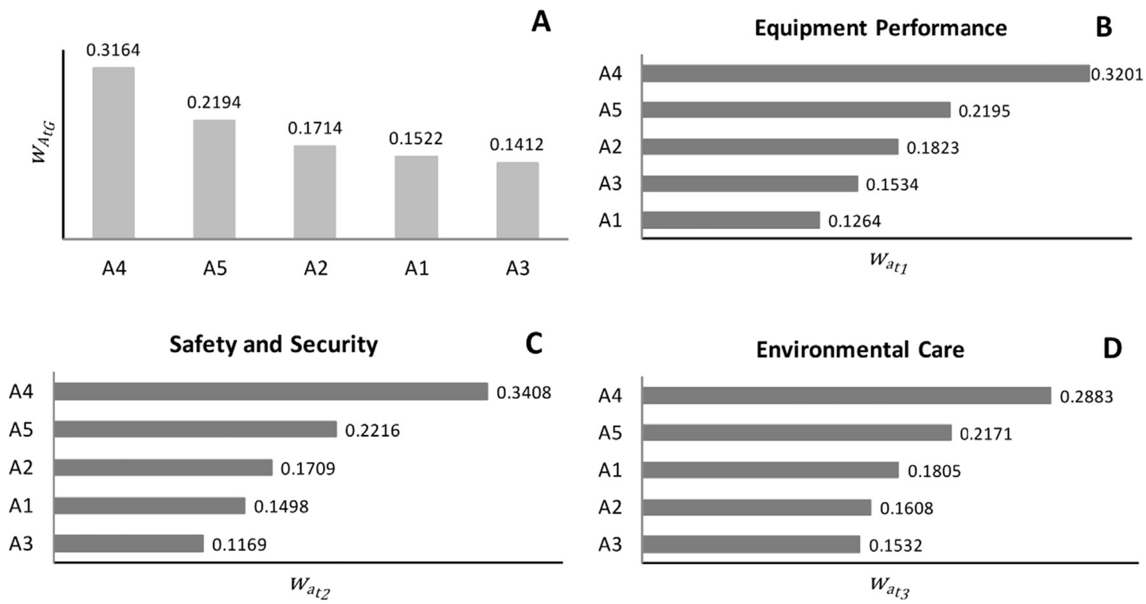


Fig. 2. Prioritization of layout, A1 – straddle carrier, A2 – forklift, A3 – reach stacker, A4 – platform and A5 – gantry crane, in terms of $W_{A_{tG}}$ (A) or $w_{a_{t_i}}$ for equipment performance area (B), safety and security area (C), and environmental care area (D).

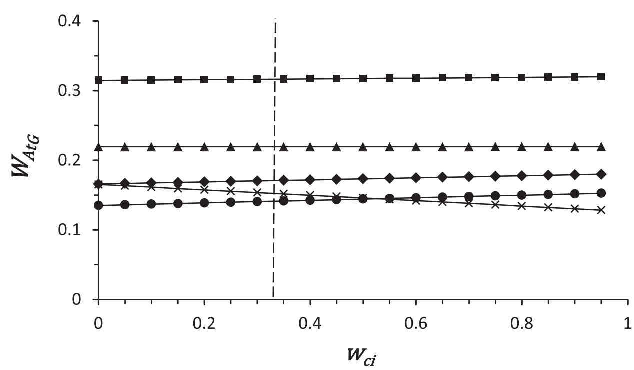


Fig. 3. Global normalized weight of the alternatives A1 – straddle carrier (×), A2 – forklift (◆), A3 – reach stacker (●), A4 – platform (■) and A5 – gantry crane (▲) related to the goal ($W_{A_{tG}}$) vs. local normalized weight for the first level criterion (w_{ci}), while varying the local normalized weight of the equipment performance area. Dotted line means w_{ci} = 0.33 for first level criteria.

performance area (Fig. 3). The preferred alternative is always a platform for any relative value of the equipment performance area, showing the robustness of the AHP method applied. There was a change in the ranking position of straddle carrier and reach stacker, but it happened for variations of w_{ci} value higher than 10%. Therefore, it should not be considered.

The model applied has demonstrated its robustness since when studying the alternative ranking variation in front of the modification of w_{ci}, the change of preferences occurred for variations of w_{ci} above 10%, exceeding the acceptable limits for a study of sensitivity.

We also studied the possible variation in the rank of preferred alternatives; this means variations on $W_{A_{tG}}$ values, when producing slight modifications on w_{ck} of the most important third level criteria. Those relevant criteria were the criteria that accumulated 80% of the sum of W_{CG_k}. We were able to verify that the alternatives A4 – platforms and A5 – gantry crane remained the preferred ones when compared with the main goal after modifying w_{ck} in values lower than 10%. Again, changes in the preference rank were not observed within the acceptable limits established for the sensitivity method.

4. Conclusion and further developments

This manuscript contributes with a decision-making methodology addressing the design of the layout of ITDGs involved in the rail transport system in order to increase the safety and environmental care of this kind of terminal without affecting drastically their operability and efficiency.

Management and storage of DGs supported by rail ITs allows a safer and greener rail transport system aimed at avoiding accidents such as Tianjin (2015) (Aitao and Lingpeng, 2017).

The main purpose of this paper is to contribute to the process of designing the layout of rail ITDGs by means of a methodology that would help designers and managers to make decisions in a systematic way. The design of the rail ITDG layout through the prioritization of the used CHE in the yard of the terminal allows us to take a holistic approach and perform global analysis from three main points of view: equipment, environmental care, and safety and security.

The AHP tool provides us with the layout generated by the utilization of platforms as the preferred option. These results have been somehow surprising since the ideal commitment alternative reached is not usual in current rail intermodal terminals.

Nevertheless results are reasonable to the extent that: (i) the rail ITDGs may be placed in not excessively expensive zones; (ii) the platforms do not require a big initial investment or expenditure on automation and maintenance; (iii) the personnel that manipulate the platforms do not require skilled training and therefore the costs are lower; (iv) from a safety and security point of view, this layout option does not generate high accumulations of dangerous substances, thereby decreasing the risk; (v) from an environmental care point of view, this alternative does not imply high consumption with its handling, or generate a high amount of waste or GHG emissions.

The implementation of this methodology will drastically reduce both the consequences in the case of a serious accident/terrorist attack and emissions of GHGs in rail ITs where containers with DGs are present, without incurring additional costs or impacting negatively on the operability of the rail transport.

The design of the rail ITDG layout through the prioritization of the CHE used in the yard has been shown to be an innovative, reliable and robust method by means of sensitivity analysis. This investigation shows a holistic model that should be applied to several case studies. We believe that it would be desirable to spread the results of this investigation among rail terminal managers and designers for a greener, more efficient, safer and more secure multimodal rail transport. Moreover, for a broader improved design of rail ITDGs, it would be interesting to evaluate ICT (information and communication technology) and BI (business intelligence) solutions using the methodology presented in this paper, together with consideration of how the CHE used in the buffer area of the terminal can affect the decision-making process regarding the CHE used in the yard of the rail terminal. Another development would be the verification of outcomes through the development of a case of study and/or discrete event simulation to measure and compare Key Performance Indicators (KPIs) for each alternative.

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Appendix A

See Tables A1 and A2.

Table A1
Global normalized weights (W_{CG_k}) for three criteria areas (equipment performance, safety and security and environmental care).

First level criterion: equipment performance		
Second level criteria	*Third level criteria*	*Weight* (W_{CG_k})
B1 Economic	C11 Automation cost	0.036
	C12 Ground cost	0.094
	C13 Personnel cost	0.014
	C14 Maintenance cost	0.029
	C15 Expansion cost	0.009
B2 Performance	C21 Containers per hour	0.003
	C22 Time for serving trucks	0.004
	C23 Use of door	0.008
	C24 Equipment inactivity rate	0.038
	C25 Time of container permanence	0.004
B3 Capacity	C31 Storage capacity	0.001
	C32 Number of lanes per door	0.003
	C33 Number of cranes per door	0.001
	C34 Number of containers moved per hour	0.009
B4 Expansion	C41 Expansion possibility	0.022
	C42 Expansion complexity	0.002
	C43 Expansion time	0.002
B5 Functionality	C51 Automation level	0.007
	C52 Usability	0.022
	C53 Scenario change	0.022
First level criterion: safety and security		
Second level criterion	*Third level criteria*	*Weight* (W_{CG_k})
B6 Safety and Security	C61 Danger level of the DGs	0.076
	C62 DG amount	0.042
	C63 Distance to the urban core	0.129
	C64 Equipment reliability	0.011
	C65 Evacuation time	0.043
	C66 Density of population	0.024
	C67 Weather conditions	0.009
First level criterion: environmental care		
Second level criteria	*Third level criteria*	*Weight* (W_{CG_k})
B7 Location	C71 Industrial ground availability	0.086
	C72 Flood risk	0.031
	C73 Available water resources	0.027
	C74 Acoustic impact prediction	0.008
	C75 Landscape impact	0.004
B8 Design	C81 Energy efficiency	0.018
	C82 Waste system management	0.008
	C83 Phreatic-level water protection	0.031
	C84 Waste storage area conditioning	0.008
	C85 Containers per waste fraction	0.002

(*continued on next page*)

Table A1 (*continued*)

First level criterion: equipment performance		
Second level criteria	*Third level criteria*	*Weight* (W_{CG_k})
B9 Management	C91 Energy efficiency	0.013
	C92 Waste minimization	0.005
	C93 Control of product transportation	0.004
	C94 Preventive measures against pollution	0.004
	C95 Water network distribution maintenance	0.001
B10 Construction	C101 Management of construction and demolition residues	0.011
	C102 Water consumption	0.038
	C103 Management of equipment, vehicles and facilities	0.005
	C104 Recovery of topsoil	0.012
B11 Emergency	C111 Adsorbent material	0.002
	C112 Procedures	0.004
	C113 Training	0.008
	C114 Weather	0.001

Table A2
Local normalized weight of the alternatives versus each third level criterion ($w_{a_{t_k}}$) value for the alternatives for the third level criteria.

Criterion	Alternative	$w_{a_{t_k}}$	Criterion	Alternative	$w_{a_{t_k}}$	Criterion	Alternative	$w_{a_{t_k}}$
C11	A1	0.0745	C51	A1	0.2672	C83	A1	0.0723
	A2	0.2573		A2	0.0385		A2	0.2594
	A3	0.1403		A3	0.0385		A3	0.1329
	A4	0.5006		A4	0.5186		A4	0.5058
	A5	0.0273		A5	0.1373		A5	0.0296
C12	A1	0.2138	C52	A1	0.0919	C84	A1	0.1954
	A2	0.0578		A2	0.2039		A2	0.0839
	A3	0.1071		A3	0.2039		A3	0.0839
	A4	0.0310		A4	0.4694		A4	0.0387
	A5	0.5903		A5	0.0308		A5	0.5982
C13	A1	0.0862	C53	A1	0.0919	C85	A1	0.0919
	A2	0.2010		A2	0.2039		A2	0.2039
	A3	0.2010		A3	0.2039		A3	0.2039
	A4	0.4691		A4	0.4694		A4	0.4694
	A5	0.0427		A5	0.0308		A5	0.0308
C14	A1	0.0723	C61	A1	0.2998	C91	A1	0.4805
	A2	0.2594		A2	0.0453		A2	0.0727
	A3	0.1329		A3	0.0453		A3	0.0727
	A4	0.5058		A4	0.0949		A4	0.0727
	A5	0.0296		A5	0.5148		A5	0.3013
C15	A1	0.0745	C62	A1	0.2615	C92	A1	0.2364
	A2	0.2573		A2	0.0634		A2	0.0876
	A3	0.1403		A3	0.1290		A3	0.0876
	A4	0.5006		A4	0.0333		A4	0.0876
	A5	0.0273		A5	0.5128		A5	0.5007
C21	A1	0.2944	C63	A1	0.0634	C93	A1	0.3085
	A2	0.0878		A2	0.2615		A2	0.0697
	A3	0.0964		A3	0.1290		A3	0.0697
	A4	0.0297		A4	0.5128		A4	0.0608
	A5	0.4917		A5	0.0333		A5	0.4913
C22	A1	0.0485	C64	A1	0.1223	C94	A1	0.5191
	A2	0.3967		A2	0.0529		A2	0.1429
	A3	0.3967		A3	0.0529		A3	0.1429
	A4	0.1098		A4	0.5140		A4	0.1563
	A5	0.0485		A5	0.2580		A5	0.0389
C23	A1	0.1347	C65	A1	0.0600	C95	A1	0.1342
	A2	0.2636		A2	0.2150		A2	0.1342
	A3	0.4955		A3	0.2150		A3	0.1342
	A4	0.0682		A4	0.4779		A4	0.0346
	A5	0.0381		A5	0.0322		A5	0.5628

(*continued on next page*)

Table A2 (*continued*)

Criterion	Alternative	$w_{a_{tk}}$	Criterion	Alternative	$w_{a_{tk}}$	Criterion	Alternative	$w_{a_{tk}}$
C24	A1	0.0745	C66	A1	0.0634	C101	A1	0.0919
	A2	0.2573		A2	0.2615		A2	0.2039
	A3	0.1403		A3	0.1290		A3	0.2039
	A4	0.5006		A4	0.5128		A4	0.4694
	A5	0.0273		A5	0.0333		A5	0.0308
C25	A1	0.1511	C67	A1	0.3136	C102	A1	0.0919
	A2	0.0464		A2	0.1093		A2	0.2039
	A3	0.0464		A3	0.0553		A3	0.2039
	A4	0.2526		A4	0.0298		A4	0.4694
	A5	0.5036		A5	0.4920		A5	0.0308
C31	A1	0.2043	C71	A1	0.2561	C103	A1	0.0993
	A2	0.0548		A2	0.0680		A2	0.2079
	A3	0.1062		A3	0.1219		A3	0.2079
	A4	0.0306		A4	0.0327		A4	0.4420
	A5	0.6041		A5	0.5213		A5	0.0430
C32	A1	0.0485	C72	A1	0.0723	C104	A1	0.2561
	A2	0.3967		A2	0.2594		A2	0.0680
	A3	0.3967		A3	0.1329		A3	0.1219
	A4	0.1098		A4	0.5058		A4	0.0327
	A5	0.0485		A5	0.0296		A5	0.5213
C33	A1	0.2432	C73	A1	0.0845	C111	A1	0.1640
	A2	0.2432		A2	0.1976		A2	0.3627
	A3	0.2432		A3	0.1976		A3	0.3627
	A4	0.0270		A4	0.4897		A4	0.0818
	A5	0.2432		A5	0.0305		A5	0.0287
C34	A1	0.0563	C74	A1	0.5040	C112	A1	0.1640
	A2	0.1092		A2	0.1079		A2	0.3627
	A3	0.1966		A3	0.1079		A3	0.3627
	A4	0.0331		A4	0.2482		A4	0.0818
	A5	0.6048		A5	0.0321		A5	0.0287
C41	A1	0.0959	C75	A1	0.5040	C113	A1	0.0535
	A2	0.2491		A2	0.1079		A2	0.3057
	A3	0.1442		A3	0.1079		A3	0.3057
	A4	0.4781		A4	0.2482		A4	0.3057
	A5	0.0327		A5	0.0321		A5	0.0293
C42	A1	0.0959	C81	A1	0.0919	C114	A1	0.3117
	A2	0.2491		A2	0.2039		A2	0.0460
	A3	0.1442		A3	0.2039		A3	0.0460
	A4	0.4781		A4	0.4694		A4	0.1030
	A5	0.0327		A5	0.0308		A5	0.4933
C43	A1	0.0959	C82	A1	0.0707			
	A2	0.2491		A2	0.1591			
	A3	0.1442		A3	0.1591			
	A4	0.4781		A4	0.5751			
	A5	0.0327		A5	0.0361			

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Glossary

AHP: Analytical hierarchical process
CBA: Cost-benefit analysis
CHE: Container handling equipment
CR: Consistency ratio
DGs: Dangerous goods
GHG: Greenhouse gas emissions
ITDG: Inland terminals of containers with dangerous goods
MCDM: Multicriteria decision making
RI: Random index
TEU: Twenty-foot equivalent unit
tkm: Tonne-kilometre
$W_{A_{tG}}$: Global normalized weight of alternative "t" related to the goal
$w_{a_{ti}}$: Local normalized weight of alternative "t" versus the first level criterion "i"
$w_{a_{tj}}$: Local normalized weight of alternative "t" versus the second level criterion "j"
$w_{a_{tk}}$: Local normalized weight of alternative "t" versus the third level criterion "k"
W_{CG_k}: Global normalized weight of criterion "k" in the third level versus the goal
w_{ci}: Local (and global) normalized weight of a first level criterion "i"
w_{cj}: Local normalized weight of a second level criterion "j"
w_{ck}: Local normalized weight of a third level criterion "k"