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Safety

One form of active prevention is to set up a series of safety barriers. The "ambient intelligence" concept has now been developed to such an extent that intelligent systems can be built up using wireless sensor networks. These systems are then capable of identifying hazards and assessing risks, as well as helping in the adoption of real-time proactive prevention measures. This study involves the design of a real-time decision-making system capable of identifying a risk situation and deciding on the corresponding preventive measure; it can also detect if a worker has suffered an accident and arrange evacuation if so. An analysis has been made of available technologies, setting up a solution that has been implemented in a prototype system. The prototype has then been put through its paces and its effectiveness assessed in a real-life scenario.

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A principle laid down in article 14 of the Spanish Occupational Risks Prevention Act (*Ley de Prevención de Riesgos Laborales*) 31/1995, of 8 November and its subsequent amendments is that «workers are entitled to an efficient health-and-safety-at-work protection. This right presupposes a concomitant duty of employers to protect their workers from occupational risks». This article also states that «employers will keep up a permanent monitoring of the prevention activity in the interests of continually perfecting and fine-tuning all activities of risk-identification, -assessment, -avoidance or, where complete avoidance is impossible, -control. Protection levels should also be continually improved. Employers shall also be in possession of all necessary wherewithal for adapting the prevention measures indicated in the above paragraph to such modifications as may occur in the working circumstances.»

In a continually changing environment such as a construction site this ongoing adaptation to risk situations is no easy task. Article 15 also identifies «keeping abreast of the evolution of technology» as one of the main preventive principles; this ipso facto implies a need for continual innovation to allow employers to phase in such technologies as might improve the occupational risk prevention performance.

This study incorporates information and communication technologies (ICT) into the improvement of prevention systems, defining new technological tools that provide the best accident-control solutions.

The construction sector's occupational accident rate is the highest in Spain: 8232 accidents per 100,000 registered workers. The Spanish Institute for Occupational Safety and Health (INSHT[1] in Spanish initials), in collaboration with regional authorities, has drawn up a study of the Causes of Occupational Accident Mortality in Spain 2005-2007 (*Análisis de la mortalidad por accidente de trabajo en España 2005-2007*), identifying the following main causes:

- Absence or deficiency of collective fall protection measures.
- Inadequate or non-existent training/information on risks or preventive measures.
- Non use of obligatory personal protection garments laid on by the employing company.
- Non-existent, confusing, contradictory or insufficient instructions.
- Breach of working instructions and procedures.

Any system capable of improving the identification of the wearing of personal protection equipment and the presence of workers in restricted zones, monitoring their situation and state and giving real-time risk information, would represent a significant technical advance, setting up safety barriers in the sector's most accident-prone areas. This system should be set up together with a proper prevention management system, suitable training and induction measures and worker awareness-raising and motivation measures.

One of the main difficulties on any construction site is access control and the concurrence of workers involved in different tasks, all of which have to be coordinated. A system like the one put forward herein would involve the creation of a second supervision loop based on active worker monitoring.

Products providing partial solutions are now cropping up but without offering any across-the-board protection. Besides this piecemeal approach, these solutions are generally of restricted usefulness on building sites because of the technology used: GSM/GPRS combined with GPS technology.

Wireless Technology

One of the project objectives is selection of the best technology for achieving the sought solution. The concept of wireless sensor networks (WSN) involves the creation of a platform of sensors and communication technology for monitoring not only physical or circumstantial magnitudes (events) within a given scenario (in our case the physical space occupied by a construction site) but also decision making.[2].

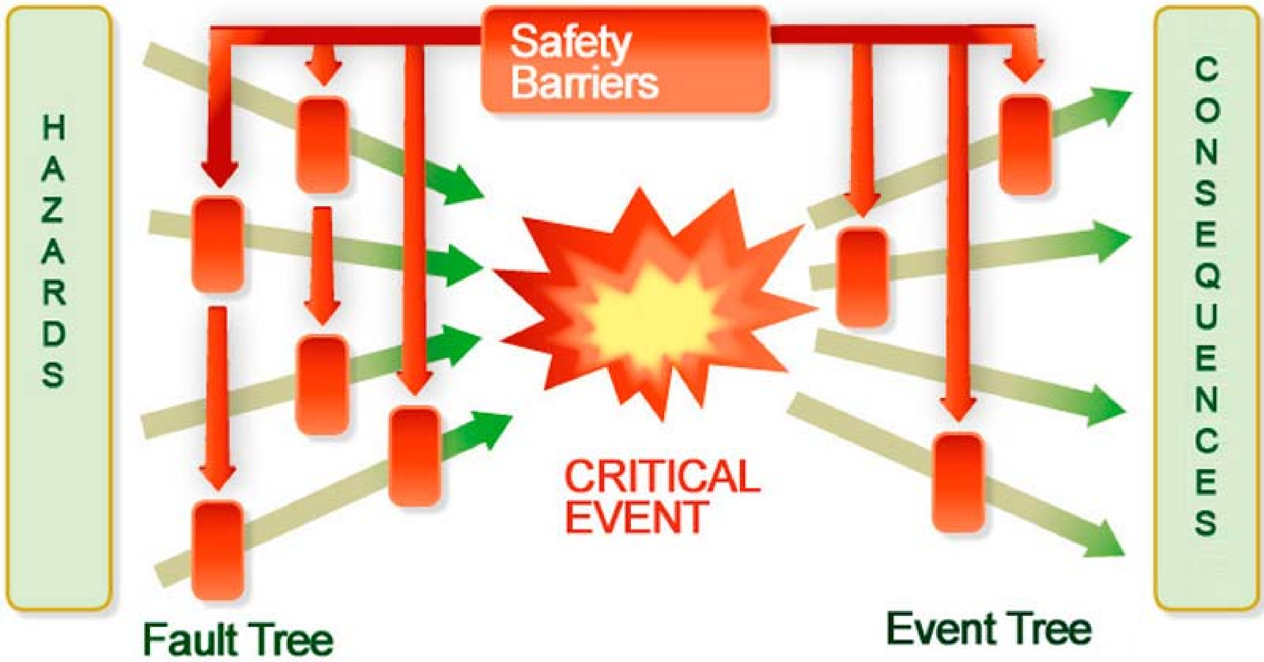
The most suitable communication system in the construction sector (both buildings and civil engineering) is wireless technology. The key reason for the use of this technology is the reduction of installation costs and the possibility of reuse on subsequent building sites, due to the lack of any cabling requirements.

The most widely used wireless modules nowadays tap into the 868 MHz band. Due to the reduced bandwidth thereof, however, there is currently a trend towards wireless systems operating in the unlicensed 2.4 GHz band. The chosen technology belonging to this band has been deemed the most suitable for meeting the needs of this project. This technology includes two short-range solutions like Bluetooth and Zigbee. The latter reaches distances of up to about 500 metres, though there are also some modules that increase this range considerably. Conversely, this is low bandwidth technology (250 Kbps).

Table 1. Comparison of technologies.

Technology	Wi-Fi	WiMAX	Bluetooth	ZigBee
Capacity	54-11 Mbps	70 Mbps	1-10 Mbps	250 kbps
No. of nodes	+100	+1000	8	65000
Autonomy	.5-5 days	Power supply	1-7 days	3-30 months
Range	10-300 m	50 km	1-100 m	100-300 m
Latency	1ms	1ms	14ms	240µs
Security	WEP 802.1x WPA	DES3 AES PKM-EAP		AES-CCM-128
Topology	Point to point	Point to point	Point to point	Point to point
	Point to	Point to	Point to	Star
	multipoint	multipoint	multipoint	Mesh
	Mesh			Tree
Modulation	DSSS and OFDM	OFDM	FHSS	DSSS

For applications needing longer range the technologies GPRS, Wi-Fi and Wi-MAX have been chosen. The idiosyncrasies of each type of construction work (civil engineering – open countryside – or building work – in a built-up area) could call for the setting up of a mixed network using several different technologies, with gateways for passing from one to the other.



Graph 1: A simplified bow-tie representation (Dianous, Fievez, 2006, p. 221; Delvosalle et al., 2006, p. 201).

ZigBee (wireless) technology is the most suitable for building applications, bearing in mind the number of nodes and sensors, autonomy, range and security.

Object and Scope

The ultimate aim of this project is to define an intelligent sensor-based, low-cost, user-friendly system capable of detecting risky situations, taking decisions and therefore favouring a proactive avoidance of occupational accidents.

Before describing the system we first need to give a brief explanation of three underlying principles:

- **Safety barrier concept.** A safety barrier is a damage-control, -limitation or –prevention function [3]. The modern, conceptual accident-prevention models, like MORT[4] (*Management Oversight & Risk Tree*), consider two main types of risk-reduction barriers to protect workers: barriers that prevent the accident from happening and those that mitigate the damage. The barriers are not necessarily physical and might be either logical systems or organisational methods
- **Active prevention.** Active prevention is condition-dependent action. A system based on the active prevention concept takes prevention measures to suit the actual situation being dealt with.
- **Ambient intelligence.** The paradigm of Ambient Intelligence (AmI) is explained in the ISTAG document –(Information Society Technologies Advisory Group), which presents a vision of the future information society, stressing user friendliness, more efficient services support, user empowerment and support for human interactions. People are surrounded by intelligent intuitive interfaces that are embedded in all kinds of objects and an environment that is capable of recognising and responding to the presence of different individuals in a seamless, unobtrusive and often invisible way. The central idea is that technology should be designed for users rather than the other way around[5][6].

The main technological requirements are:

- Unobtrusive hardware: miniaturisation and nanotechnology, smart devices, embedded computers, power supply, sensors, activators …
- Continuous information infrastructure based on landline and mobile web access.
- Networks of dynamic and distributed devices, interoperable devices and bespoke configurable networks, network embedded intelligence.
- Lifelike human interfaces: smart agents, multimodal interfaces, context sensing models.
- Reliability and security: robust and reliable systems, self-checking, self-repairing and self-organising software.

The sensor-based intelligent system defined by this project is therefore an active prevention system involving the implementation of ambient-intelligence type safety barriers. The key to success is the development of user friendly, responsive, interconnected, context-sensitive, transparent and intelligent technologies and systems.

Functionalities and Architecture

Functionalities: ambient-intelligence based design

The system is based on embedded processing power in the various objects of the system, mainly in the wireless elements. In other words the various wireless elements – the static elements (environmental and location sensors), mobile elements (tracking and monitoring of the workers' vital signs) and semi-static elements (tracking and monitoring of machinery operation conditions) – would act as intelligent cooperating objects embedded in an ambient-intelligence system.

The main functionalities to be offered by an ambient-intelligence-based system are:

- **Detection of the site personnel's situation and location.** The capacity of detecting person-related data such as their mobility, location, state (for example, detection that a worker is not moving because he or she has suffered an accident or has fallen, etc.) is one of the new possibilities offered by the system to be developed. This is an activity based wholly on the sensor network's capacity of capturing ambient information. It also allows detection of unauthorised personnel on site or in certain areas.
- **Detection of factors affecting the system.** The sensor network identifies exposure to toxic and hazardous environments, to situations of poor visibility or adverse hydrothermal conditions.
- **Capacity of acting in hazardous circumstances.** The system response may consist of giving out alarms to the safety-coordination resources or to the worker him/herself or the tripping of protection elements (lighting, ventilation, speed limitation or steering guidance of equipment and machinery, etc).
- **Active signage.** The system gives out active and sensible information on the site situation, the surrounding environment, the situation of other workers and their state.
- **Detection of emergency situations.** The installation of different types of onsite sensors enables emergency plans to be activated on the basis of the information obtained.
- **Remote site-monitoring capacity.** Depending on the type of attributes to be controlled on each type of site, it may or may not be necessary to set up remote, real-time monitoring, especially in cases where the working processes to be controlled might trigger emergency situations or when the coordination resources – due to the size or complexity of the site – need remote situation information (tunnels, high-rise buildings, etc).

Basic System Architecture

The basic intelligent infrastructure for setting up the communications network and processing the information comprises the following items:

- **Nodes**
  - **Static facilities.** These will be considered as the main constructive elements of the infrastructure. They will be fitted with wireless sensors capable of picking up information about the surrounding environment, embedded software capable of processing the captured information using intelligent algorithms and communication devices capable of sending on the information to other system items.
  - **Mobile or semi-static elements of each type of site.** These will be similar to the static elements and, depending on their geographical situation, might be fitted with the same sensors as the former. They shall be fitted with embedded software capable of processing the sensor-captured information and also equipment for sending on this information to other system elements, bearing in mind that their location might not always be known beforehand.
  - **Gateway or coordinating node.** This will be considered as the main element for processing the data sent in by the rest of the intelligent system elements. It will be an open source development, able to monitor this information and interact with system elements. The gateway's main function will be site monitoring. It will, however, receive much more information, such as environmental agents, system-affecting factors, etc, plus all safety-related aspects. Finally, the gateway will endow the system with the capacity of two-way communication with the outside.

- **Physical layer.** The communication network links in this system will never need a capacity of more than 100 Kbps. This is because the sensors' data-taking cadence is high in comparison with the sample taking of other applications, where data evolution is very swift. Nonetheless the data in applications of this type are unlikely to undergo any change in a short period of time. The physical layer will have to offer sufficient wireless sensor connectivity to match the nodes

forming part of the intelligent structure developed herein. A sufficient wireless communications network, connected up to all system nodes, shall exist for transmission of all processed data.

- **Middleware Layer.** This will comprise connectivity software offering a set of services. These services will facilitate running of the intelligent system's distributed applications on the created platform. It functions as a distributed software abstraction layer and lies between the applications layer and the physical layer. The main task of this layer is to render all the following transparent to the applications layer: the low level details of the hardware, of the operating system and, especially, the data distribution details through a distributed infrastructure. It hence provides a high level programming interface that can be used for external applications or for interaction with other infrastructure. From the complexity and heterogeneity of the communications network developed herein, the Middleware layer abstracts a hybrid wireless network of embedded systems. This will facilitate the possibility of real-time connection/disconnection of nodes to the network.
- **Applications Layer.** The applications layer develops the system's required functionalities. These functionalities, already described above, refer to different active-prevention aspects to be implemented.

Prototype Components

- ***Transreceivers*.** The chosen models, with inbuilt RF modules, are based on the Freescale technology.
- **Sensors.** Some (not all) of the possible sensors have been selected. Likewise, in system implementation, not all sensors are integrated into all the nodes (for example, the nodes linked to the infrastructure where the work is carried out do not include the accelerometer). Nonetheless the sensors considered herein have enabled performance tests to be conducted.
- **Temperature Sensor.** A low-consumption sensor with a two-line digital communication interface has been chosen. This device can operate in a temperature range of -40 ºC to 125 ºC, with a resolution of 0.05 ºC.
- **Accelerometer.** A digital output 3-axis linear accelerometer has been chosen, incorporating a sensor and digital interface capable of giving information on the sensor and providing an external signal of the acceleration reading through a serial interface. The device can be set to generate an inertial wake-up/free-fall interrupt signal when a programmable acceleration threshold is crossed in any of the three axes.
- **Luminosity sensor.** A low consumption sensor with digital interface has been chosen. The device transforms the luminescence (ambient light readings in lux) into a digital output signal accessible by means of the I2C bus.

Development of node prototypes

Two types of hardware-referenced nodes have been developed: static coordinating nodes and mobile nodes. The main difference between both is that the mobile node has a three-axis accelerometer. The basic structure of the first type of node consists of:

- *Transreceiver.*
- Temperature sensor.
- Accelerometer (mobile node).

For the second node version a transreceiver with external antenna was chosen, giving a higher working range and allowing the final node size to be slightly larger. A luminosity sensor was built into this node.

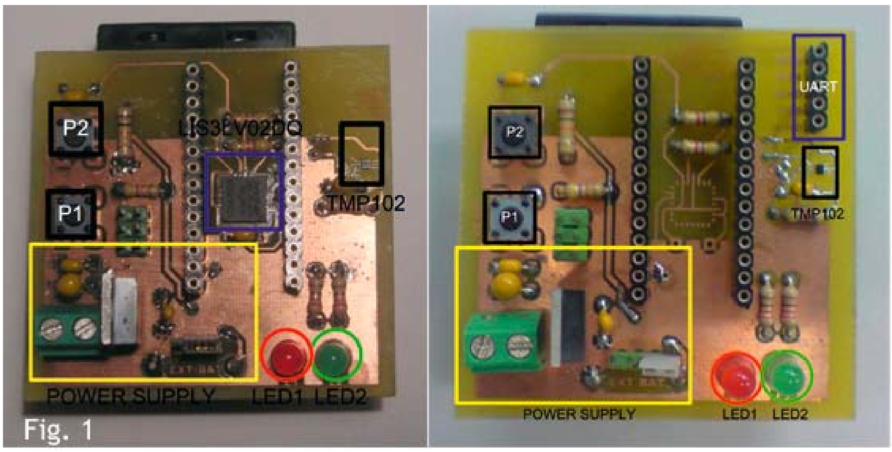


Figure 1. First prototype. Static and mobile nodes. **Figure 2.** Second node prototype.

Prototype tests and results

Design of testing scenario

In this chapter we aim to demonstrate the feasibility of the selected active worker-monitoring technology (IEEE 802.15.4 and Zigbee). The chosen scenario was simplified to allow the test to be carried out in the framework of this project and also in view of time- and budget-limitations.

In the proposed scenario we will assess the system's capacity to identify a worker's position, using an accelerometer to check the subject's activity and any changes in his or her state. The system consists of mobile nodes (workers) and static nodes (construction site). The static nodes have a dual function: give coverage to the infrastructure and serve as a reference for ascertaining the position of the mobile nodes. Furthermore, there is a central or coordinating node, which culls information and sends it on to the management computer (figure 3).

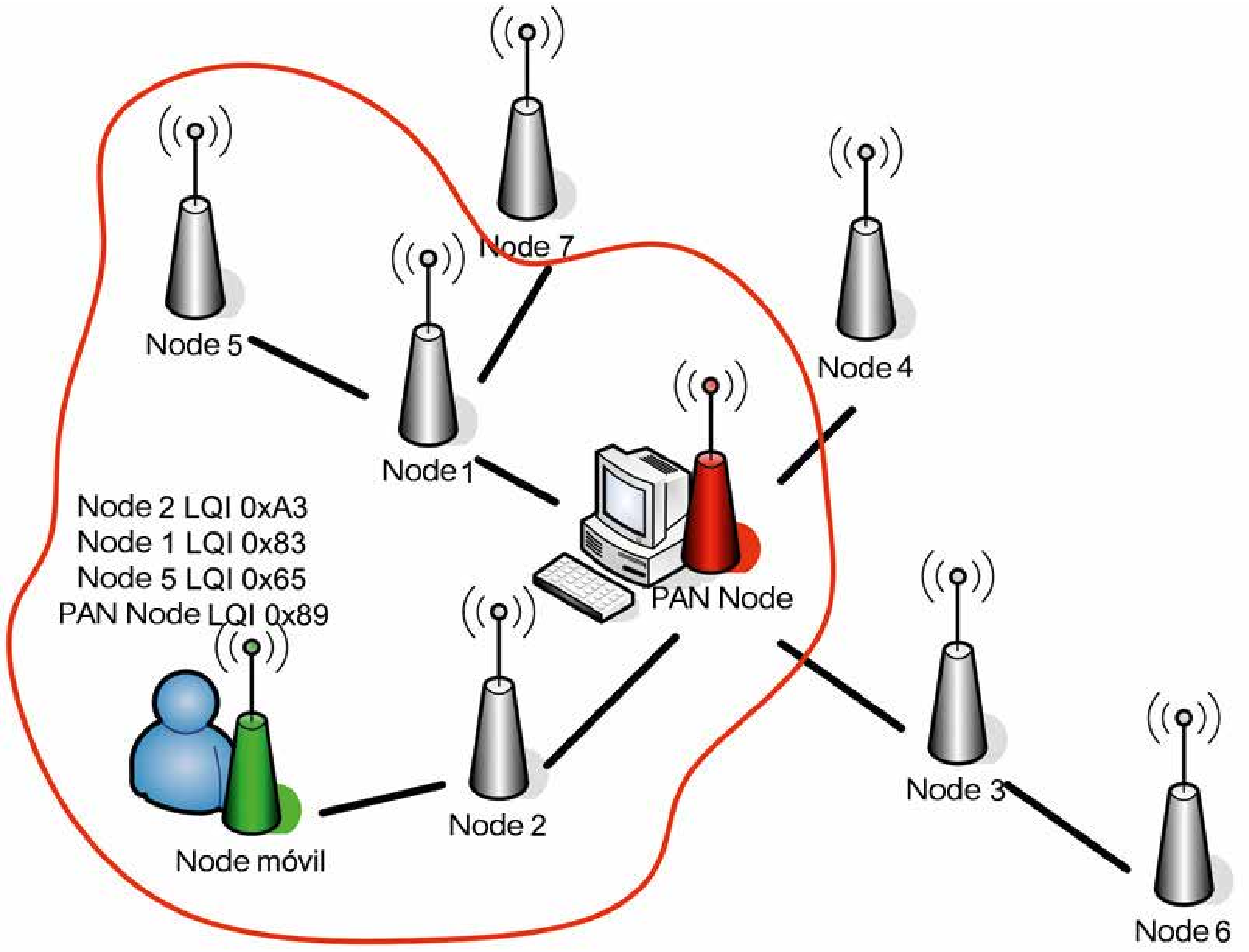


Figure 3. Network Architecture.

The coordinating node, shown in red in the diagram, is connected up to a central server. There is also a node infrastructure deployed throughout the site (for example, nodes fitted in the luminous signage) to increase the coverage zone. These will serve to locate the worker (given that the position of the infrastructure is known, we can compute by triangulation the worker's position using the Link Quality Indicator or LQI, whose reading shows the distance between devices and hence the relative location according to signal intensity).

To conduct the tests in the scenario, various nodes had to be manufactured:

- **Reference Node.** This node has a fixed and known position. It is configured with X and Y coordinates corresponding to its location. It single task is to await a Broadcast message (i.e., to all of them) with the LQI reading and then send it on to the coordinating node. The reference nodes communicate with the sensor nodes and with the coordinating node of our network.
- **Mobile Node.** This node will send out a Broadcast message whenever it needs to ascertain its network position. It is also fitted with an accelerometer to monitor the worker's situation and movements.
- **Coordinating node.** This node receives the messages from the sensor nodes and stores them in an LQI readings table for each sensor node. Once the address of the reference node is known, it will access a table where the corresponding fixed address of this device is stored. Working from these input parameters it will then estimate the location of the

device by means of the localisation algorithm. Once this position has been obtained it will be sent on to the coordinating node.

Network functioning

The implemented system was assessed by means of the following tests:

- Network functioning tests, e.g., acknowledgements, relays, Multicast messages, network self-organisation, etc.
- Worker tracking tests (mobile node).
- Worker event monitoring tests (mobile node): worker activity level, falls, etc.

> *The key to success lies in the development of user friendly, responsive, interconnected, context-sensitive, transparent and intelligent technologies and systems*

A programme has been designed to manage the sending and receiving of messages between the radio modules issued to each system member. This message management will be geared towards providing the coordinating equipment or node with the necessary real-time information to give it an overview of the location and state of the mobile node (worker).

- **Coordinating Node.** This node starts with an energy detection scan to choose the best channel for starting the Personal Area Network (PAN). Once the network has been started, the coordinator switches to reception mode to await association requests from other nodes and network node data. The coordinator controls the network nodes by tripping a meter. When the meter has finished counting, it checks the nodes from which it has received information messages. A missed-message meter will then be started for all nodes from which no information has been received. Any node for which three successive missed messages are detected will be assumed to have lost connection and will then be removed from the list of network nodes.
- **Sensor Node.** Sensor nodes are considered to be all those other than the coordinating node and mobile node, as distributed around the scenario covering the range of the latter.
  Sensor nodes are continually in a message waiting loop. These messages may be of two types: Broadcast messages and messages relayed from other nodes. We will look first at how the former are managed. The sensor node receives a Broadcast message from the mobile node; from the data packet in that message it obtains the LQI reading between both.
  The rest of the messages received by the sensor mode will be Unicast. If the message received comes from another sensor node, it will contain the LQI readings of the node it comes from and of the corresponding nodes associated therewith. The only thing it will do with such a message, therefore, is add the LQI reading of the sensor node and send it on to the node it is associated with until it reaches the coordinating node. The sensor node also sends information on ambient temperature and the light level of its corresponding area.
- **Mobile node.** The application designed for the mobile node limits itself to sending the information obtained from the sensors and sending a Broadcast message so that the other nodes can obtain the LQI reading of the respective links. The abovementioned algorithms are implemented for information processing purposes.
  A 3-axis accelerometer has been used to find out the state of the mobile node. The worker information provided will be threefold: the temperature, whether or not the worker is breathing (by processing the accelerometer information) and if he or she has suffered a freefall. This will give rise in turn to three different worker states: ACTIVE, ALARM (sudden movement) and EMERGENCY (no movement at all).

Network functioning tests

The implementation tests involved final system tests and then successive tests during the development period. A description is now given of the tests carried out during system implementation:

- **Association with a network device.**To check a final device’s capacity of linking with a PAN, the test consisted of the coordinator initiating a PAN upon start-up. When the final device starts up and one of the board buttons is pressed, it will automatically scan the frequency channels in search of a network and associate with it. The final device seeking network association chooses one of the PAN coordinators that have been found during the scan.
- **Data sending and reception.** To check the capacity of sending messages from one device to another, the addresses assigned to each device are stored and then used for sending a message from one device to another. The receiver will remain in data reception mode while it is not busy.
- **Range.** The prototype node boards offer a range of about 800 metres in direct vision; in indoor spaces this is cut down to 200 metres.

- **Node control and acknowledgement.**To control network nodes each device has a table of associated nodes (child nodes). To monitor permanence it will receive a message from each child node every set period of time. For its part each child node will have to check that it has received acknowledgement of messages sent to the coordinating node. Missed messages are relayed and a check is kept on the number of relay attempts; if these exceed a set limit the device will reset and try to associate with the network again, either with the former coordinating node or a new one within its range. The system thus resets in the event of losing any network node.

Localisation of mobile nodes

The localisation algorithm used is based on the LQI (Link Quality Indicator), whose reading varies inversely with the distance between the devices. Various types of localisation algorithms have been developed.

One of them, used in the first network prototypes, was based on the sending of a Broadcast message. The other algorithm used is based on carrying out a scan to find the nodes neighbouring the mobile node, thus cutting down message traffic, limiting itself to sending on the reading of the nearest nodes. Both algorithms are based ultimately on the quality reading of the inter-node link. Good localisation therefore depends on knowing the position of the various static nodes.

The coordinating node receives all the messages from the static nodes and sends them on through the information packets using the PC interface. According to these readings an estimation will be made of the location of the mobile node (worker).

The LQI readings are obtained by the scanning operation carried out by each node each set interval of time. The result of the scanning is a series of neighbouring static nodes identified by the node's dual MAC address and the LQI reading. The mobile node sends a message with the LQI readings of each neighbouring node to the network coordinator. The mobile node therefore sends to the coordinator only the LQI readings of the nearest nodes, thus cutting down message traffic. If a node's LQI reading is not sent, this is because the node is sufficiently distant to be outside the mobile node's scanning range.

It may so happen, however, that, remaining in the same place, a mobile node does not scan all nearby nodes. This is because the mobile node remains in scanning mode a set interval of time and not all the nodes may respond to the initial scan. For this reason the best way of managing mobile node tracking in the control gateway connected to the coordinating node is by averaging out all the LQI readings of each static node every few seconds, when several node-related LQI readings have been taken.

The test results are not sufficiently precise (by about one or two metres) when using only the LQI, so an algorithm will have to be developed in the future using also the wave propagation time, which is insensitive to obstacles. The obtained precision allows the worker zone to be demarcated (inside the static nodes corresponding to their location) but not his or her position within this zone. This is due to the fact that the LQI reading might deteriorate depending on the presence of obstacles.

Worker Monitoring

The mobile node will have to be fitted with an accelerometer to provide readings of vital signs and/or falls.

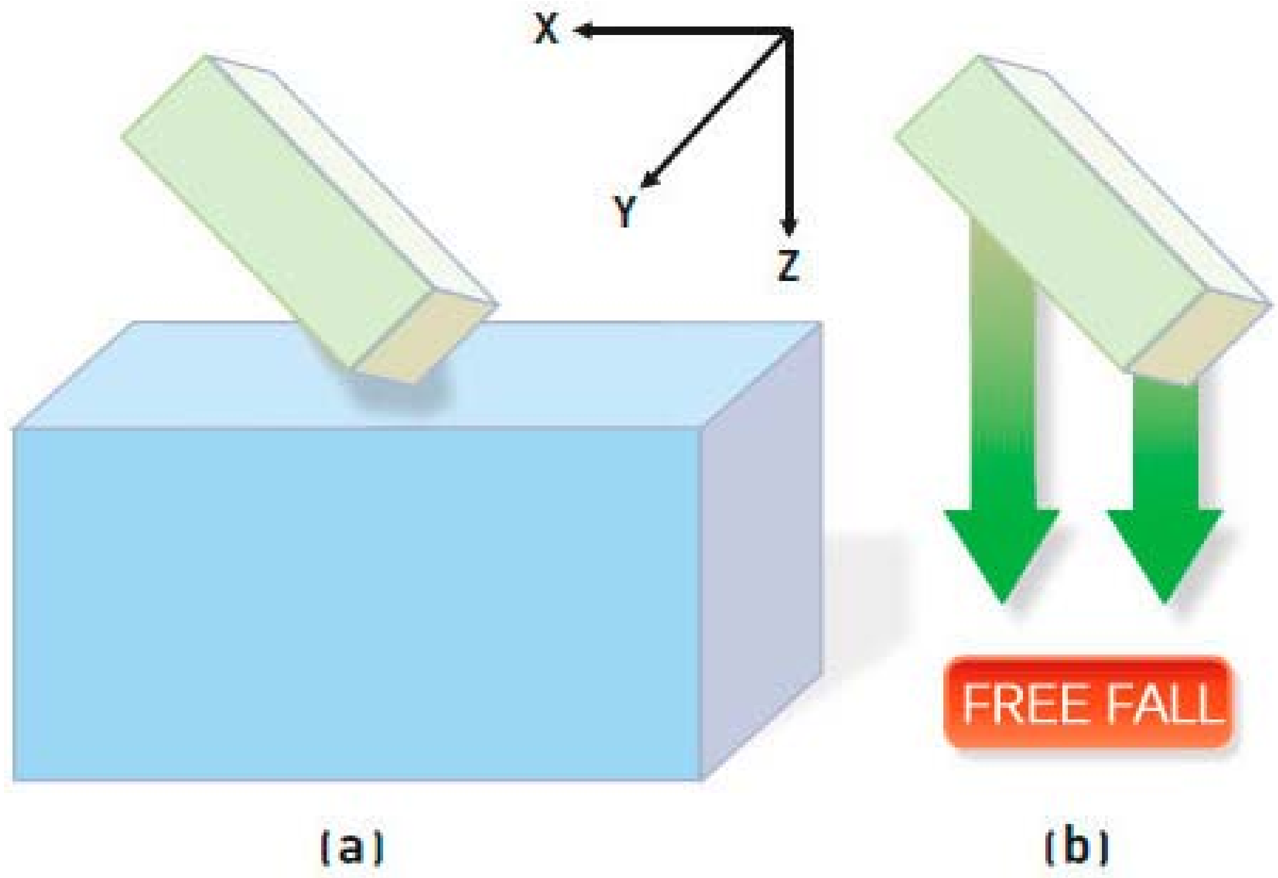


Figure 4. Freefall Model.

Detection of free fall. Take the case of a node with an arbitrary orientation (figure 4). Its axes form the angles α with respect to the x axis; β with respect to the y axis; and γ with respect to the z axis. On this basis the accelerometer outputs are:

$$X_{OUT} = X_{OFFSET} + \left(\frac{\Delta V}{\Delta g} \cdot 1g \cdot sen\alpha\right)$$

$$Y_{OUT} = Y_{OFFSET} + \left(\frac{\Delta V}{\Delta g} \cdot 1g \cdot sen\beta\right)$$

$$Z_{OUT} = Z_{OFFSET} + \left(\frac{\Delta V}{\Delta g} \cdot 1g \cdot sen\gamma\right)$$

where:

VOUT = Accelerometer output in volts

VOFFSET = Offset reading at 0 g of the accelerometer

ΔV/Δg = Accelerometer sensitivity

1 g = Earth's gravity

When the object falls, the acceleration reading in all three axes is zero, regardless of the object orientation, because no acceleration will be detected in any axis. This is so, as already explained, because the accelerometers fall with the same acceleration as that exerted by the force of gravity.

The free-fall detection algorithm samples the accelerometer readings and supervises these acceleration rates. Depending on the orientation, each accelerometer will have an acceleration range between 1 g (when the accelerometer axis lies parallel to the gravitational force) and 0 g (when the axis lies perpendicular to the gravitational force). The S-factor is a way of considering the total acceleration acting on the device at a given moment of time.

$$S - factor = \sqrt{X^2 + Y^2 + Z^2} \leq umbral$$

During freefall the three axes will all detect 0 g. As the S-factor is defined by the total acceleration in all three axes and these accelerations all equal 0, the S-factor will also equal 0. Election of the threshold value will depend on the system response times, the precision of the A/D converter and the characteristics of the accelerometers, such as sensitivity, offset, variation with temperature and the number of samples taken and type of algorithm. This threshold has been determined experimentally as lying between 1 and 100 ms (figure 5).

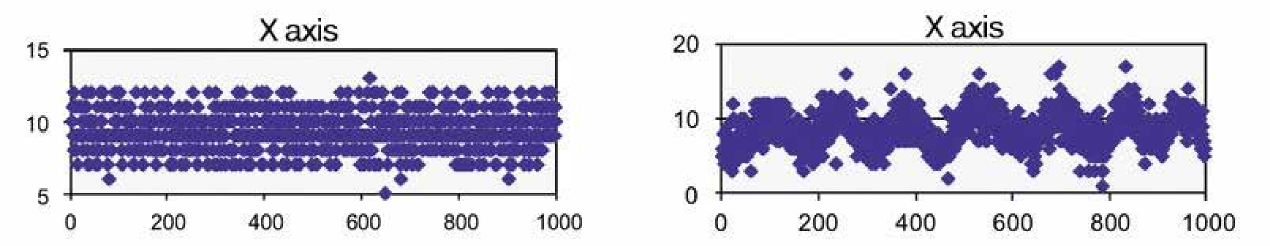


Figure 5. Accelerometer response differences (the righthand graph shows the readings when worn by the worker).

Detection of worker's vital signs

Certain accelerometer readings tell us whether the worker presents any signs of activity, triggering an alarm if not.

The oscillation frequency is low so the sample acquisition time was set at 40 ms and at least 200 samples will be necessary to obtain a signal period. Accordingly, the time needed for diagnosing the user state is 8 seconds. The threshold choice is crucial because there might be time when the worker is at absolute rest, tripping a false alarm for lack of vital signs. The results obtained are sufficiently robust despite the accelerometer's low sensitivity and the A/D converter's quantization noise.

Conclusions and future developments

The results of the experiments show that it is possible to design an active accident-prevention system from a wireless sensor network organised under a scheme of ambient intelligence.

Some functions such a fall detection or the monitoring of vital signs are clearly possible, while others, like tracking, need some fine tuning. In a construction-site-sized scenario direct communication between all nodes is possible, using the natural coverage extension provided by IEEE 802.15.4 technology. Even so, a network has been designed that resets itself in the event of communication losses, duly notifying the user of this.

With the current state of technology this system is feasible and affordable, especially in view of the fact that it can be reused from one site to another. The solution proposed herein does not currently exist on the market, so this study represents a starting point for its pre-competitive development. These future developments could enlarge the basic architecture as tested here and graft on systems based on IP camera vision, risk zone access control with RFID or the identification not only of personnel but also of their equipment and machinery.

It is possible to design an active accident-prevention system from a wireless sensor network under the aegis of artificial intelligence

As for the mobile node (worker) tracking system, it has not proven possible to implement the required algorithm. The aim was to monitor the approximate node coordinates in the scenario, finding out the dimensions of the latter with a triangulation algorithm with LQI readings of the sensor nodes, but these readings largely depend on node orientation. The system therefore estimates only the worker's current zone but not his or her actual position therein with submetre precision. A possible improvement here might be to increase the number of the infrastructure's static nodes (boosting system redundancy) or tag on other calculation algorithm parameters (such as wave propagation delay). Be that as it may, the first results are very promising.

As for worker monitoring, the results are acceptable in spite of low accelerometer sensitivity and A/D converter resolution. Satisfactory results have been obtained in terms of worker state patterns. Customising the hardware from here and using the peripherals best adapted to the application concerned would ensure a reliable system with significantly improved results.

ACKNOWLEDGEMENTS

This work has been funded by a FUNDACION MAPFRE research grant.

TO FIND OUT MORE

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Pre-empting fire risk

Fire safety

This study develops specific models for estimating and forecasting fire risk based on a combination of time series analysis and remote sensing data. The risk indices used in this procedure are the FPI_{NDWI} and the FPI_{NDVI}, which differ in terms of the vegetation index used in their calculation, NDVI or NDWI. The FPI (Fire Potential Index) pools meteorological data with information from remote sensing images. Time series analysis has unearthed dynamic patterns in fire behaviour during the study period 2000-2009. From the time series for the period 2000-2008, specific forecast models were developed for the two indices by «fuel type-bioclimatic region». The results show a good fit between the original FPI_{NDWI} data and the forecasts for 2009. The study also shows that the FPI_{NDWI}'s risk forecasting accuracy is better than the $FPI_{NDVI's}$, especially for the ecosystems of the north of the study region.

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Fire is considered to be a natural component of many ecosystems. Mediterranean ecosystems in particular have been heavily fire-adapted over time. Human pressure, however, has distorted this natural balance. The ecosystems can no longer cope with the sheer number of fires that break out and the vast area burnt, and are now suffering a grave environmental damage in terms of species make-up and biodiversity.

Fire behaviour is governed by three natural factors: fuel availability, the lie of the land and the weather[1]. For a fire to break out there must be sufficient biomass, the environmental conditions must be suitable and there must also be some source of ignition.

Although sociological factors weigh heavily on fire occurrence[2], fires in Spain, especially the big ones, tend to break out in summer, showing that the prevailing weather does play a key role. At this time of year the accumulated biomass becomes an easily combustible fuel under the right conditions. The fuel's availability and water content therefore also play a key role in fire outbreak. Furthermore, while the sociological and meteorological factors are very difficult to control, the former being hard to predict and the second inevitable, direct action is possible on the fuel by means of a suitable

management of silvicultural work[3]. The working hypothesis of this study is therefore that fuel type is a fundamental risk factor; the risk is also modulated by vegetation response to weather fluctuations, a highly variable factor.

Fuels can be described in terms of type, load and state. The fuel type is a static characteristic intrinsic to the fuel itself, whereas load and state are dynamic variables that vary throughout the year. These variations might be daily, seasonal or annual. Daily variations are responses to the changing weather conditions; seasonal variations are governed mainly by the biophysiological cycle of the fuel and cumulative weather effects while annual variations are the system's response to the plant species' growing cycle[3].

Identifying the high fire-risk areas, and also understanding their dynamic over time, is essential for the prevention, control and management of woodland. This identification process also furnishes a useful tool for assessing ecological conditions, since many of Spain's ecosystems are moulded by the effects of wildfires[1] . This type of analysis favours a better understanding of how variables like climate and vegetation exert a dynamic influence on fire behaviour[4], but it is a complex task since these variables all have different variation scales. Hence the need for defining specific forecasting models for each climate-vegetation combination showing different fire behaviour.

The time pattern of wildfires can be analysed by means of the risk indices, used to estimate the likelihood of a fire breaking out. The indices most widely used in Spain depend only on the weather conditions; nonetheless in Spain's geographical conditions it has proven very hard to forecast the number of fires or area burnt in terms solely of the weather. The Fire Potential Index (FPI)[5] is a dynamic fire risk indicator combining information on fuel type, weather information and vegetation state, provided by remote sensing images. The FPI has been successfully tried and tested in very different geographical areas. Several authors[6,7 and 8] have shown the usefulness of this index for describing wildfire behaviour in temperate and Mediterranean regions. Other authors[9] have drawn up an FPI-based statistical model for forecasting the number of large fires, thus demonstrating this index's capacity for estimating and forecasting fire occurrence.

IDENTIFYING HIGH FIRE RISK AREAS AND ALSO UNDERSTANDING THEIR DYNAMIC IS ESSENTIAL FOR FIRE PREVENTION AND THE MANAGEMENT AND CONTROL OF WOODLAND

The space-time coverage of some remote sensing systems makes the information supplied especially suitable as an indicator of the vegetation state within the risk indices. The multispectral images are generally analysed using vegetation indices, which are reflectance ratios at different wavelengths and depend on the specific properties of the vegetation. The most widely used spectral indices are the NDVI (Normalized Difference Vegetation Index)[10], related to photosynthetic activity, and the NDWI (Normalized Vegetation Water Index)[11], more dependent on humidity.

Time series analysis (TSA), in its frequency-domain methods and time-domain methods[12], offers a highly useful forecasting tool in nearly all areas of knowledge in which a magnitude can be measured with a given frequency, ranging from economics to engineering or meteorology. For wildfires it has been used, among other aspects, to study the area burnt per year[13], to monitor fuel humidity and assess fire risk[14], verify the dominant fire cycle[15], or to identify pre- and post-fire vegetation trends[16]. TSA furnishes us with a series of tools for pinpointing the time patterns that determine the past and present dynamic of a given variable. It also offers us a methodology for building up forecasting models based on well-defined statistical models, such as AR (autoregressive), MA (moving average), ARMA (combining the two former) and ARIMA (autoregressive integrated moving average, incorporating an integration term to establish the variable's stationarity). In reality it is not a single model but rather a set of possible models. The estimation procedure is a trial and error process to find the model that best fits the selected variable. These models have been used in various environmental fields such as hydrology[17] and in climate change studies[18], among others. These models may be used to study, analyse and model the behaviour of a variable and also to forecast its future value. Several authors[19] use an ARIMA Model to forecast drought in China.

The objective of this study is to develop specific or local fire-risk forecasting models by means of time series analysis. The fire risk is estimated using the Fire Potential Index proposed by Burgany et al (FPI_{NDVI}) and the modification proposed by Huesca et al[8] (FPI_{NDWI}).

Study Area

The study area is the *Comunidad Foral de Navarra* (Region of Navarre), which occupies an area of 10,420 km^2 and lies on the borderline of the temperate (or Atlantic), Alpine and Mediterranean bioclimatic zones. Within each ecoregion the

climate characteristics are sufficiently alike to ensure similar behaviour in terms of soil evolution and climax woodland, and therefore different fire behaviour within each one.

The Atlantic region is characterised by a warm temperate maritime climate, heavily influenced by the Cantabrian sea, with high rainfall, mists and drizzle and mild temperatures. The climax woodland in this region is deciduous. Fires are frequent but typically small in area. They have a bimodal distribution with two peaks, one at the start of spring and the other in summer-autumn.

The Alpine region can be broken down into two zones: the first, higher up, with a cold, humid continental climate and the second, lower down and closer to the borderline with the Mediterranean region. The latter is in fact a transitional area between the cold Mediterranean climate and temperate Mediterranean climate. The predominant woodland in the Alpine region is conifer and beech with a low fire frequency and a marked seasonal and annual variability.

THE WILDFIRE TIME PATTERN CAN BE ANALYSED BY MEANS OF FIRE POTENTIAL INDICES FOR CALCULATING THE LIKELIHOOD OF A FIRE BREAKING OUT

In the Mediterranean region the climate is Mediterranean as a whole but with a clear Atlantic influence in the western part verging into continental towards the east. The typical woodland of this region is sclerophyll Mediterranean, with an intermediate fire frequency likely to affect middling to large areas. The distribution of the fires is unimodal with a single peak in summer.

Materials and methods

- *Remote sensing information*
  The remote sensing information used consists of a set of 454 images captured by the MODIS sensor (MODerate resolution Imaging Spectroradiometer) onboard the TERRA satellite (https://lpdaac.usgs.gov/). The product used is the MOD09A, consisting of surface reflectance images taken in the spectral zone ranging from blue to SWIR channels. The images used have a spatial resolution of 500 metres and are 8-day compounds, making up 46 images per year, i.e., 46 values for each pixel making up the image. The study period ran from February 2000 to December 2009.

  The images were downloaded from NASA's server and were reprojected on the UTM30N projection system WGS-84 datum. The time series were built up from the extracted red (648 nm), near-infrared (858 nm) and SWIR1 (1240 nm) channels. This gives reflectance time series at three wavelengths during a 10-year period and about every 8 days. Finally, the NDVI and NDWI vegetation indices were calculated (equations 1 and 2), to be used for calculating the fire potential index FPI.

$$NDVI = (\rho_{nir} - \rho_r / \rho_{nir} + \rho_r)$$

  (Eq.1)

$$NDWI = (\rho_{nir} - \rho_{swir1} / \rho_{nir} + \rho_{swir1})$$

  (Eq.2)

  where ρ_r, ρ_{nir} and ρ_{swir} represent the reflectance in red, near infrared and SWIR1 channels respectively.

  The series were smoothed as far as possible by identifying and filtering out any outliers, using thresholds defined in terms of the mean and standard deviation of the time series. The outliers were replaced by the mean between the value of the previous date and the next date. If the previous or next date were also outliers, the first non outlying value was used.

- *Meteorological Information*
  The meteorological information was taken from the existing meteorological stations in the *Comunidad Foral de Navarra* and in the bordering provinces. The latter were tapped into to ensure a good quality of information in the borderline areas of the study. The daily readings from the meteorological stations of the *Comunidad Foral de Navarra* for the period 2000-2009 were furnished by the *Departamento de Desarrollo Rural y Medio Ambiente* (Environment and Rural Development Department) of the *Gobierno de Navarra* (Regional Government of Navarre). The meteorological data from the stations of the bordering provinces was obtained from the 17 meteorological stations of the State

Meteorological Agency (*Agencia Estatal de Meteorología: AEMET*). Since 2000 the number of available stations in Navarre has been increasing so the maximum number was used each year in the interests of obtaining the best possible results.

The variables used were maximum temperature and minimum relative humidity each day to work with the most adverse wildfire situation. The daily data was summarised to 8 days to tally with MODIS 8-day data. A calculation was therefore made of the mean value of maximum temperatures (Tmax) and minimum relative humidity (Hrel) of the 8 dates corresponding to a MODIS compound. Tmax and Hrel were the spatially interpolated date-to-date to build up maps of Tmax and Hrel for each date of the study period. The temperature was interpolated using the inverse distance method and minimum relative humidity by means of a multiple linear regression according to equation 3.

$$H_{rel} = 72.1761 - 1.4181 x T_{max} + 0.0049 x H$$

(Eq.3)

where H is the height (taken from the digital land model of Navarre).

- *Auxiliary Information*
  Other resources used in the study were the Digital Elevation Model (www.ign.es) and the Navarre Fuel Map (www.marm.es). The latter is based on the 13 fuel models established for the NFDRS (National Fire Danger Rating System) and duly adapted to Spanish vegetation. In Navarre all the fuel models are present except for those in which the fire propagation mechanism is logging slash. Each fuel model is associated with an extinction moisture, which is the moisture level at which the fire will no longer spread; this parameter is used in calculating the FPI.

- *Calculation of the Fire Potential Index (FPI)*
  The Fire Potential Index (FPI) is expressed as follows:

$$FPI = 100x(1 - Hcm_{10hrfrac})x(1 - CV_{cor})$$

(Eq.4)

where FPI is the Fire Potential Index, which takes maximum values of 100 when the risk is very high and values close to zero or negative when there is no risk. FMC10hr represents the moisture content of the small dead fuel and LR is the live ratio of the combustible fuel charge.

The indices used were the FPI_{NDVI} and FPI_{NDWI}. The FPI was calculated on the basis of the formulation described by Huesca et al[8].

- *Time Series Analysis (TSA)*
  First of all a qualitative study was made of the FPI trend over the period 2000-2009 for four zones with a vegetation type and fuel model representative of the region. A quantitative time series analysis was then carried out[12]. The time series of FPI_{NDVI} and FPI_{NDWI} of each pixel were grouped by their behaviour using descriptive statistics (mean and variance) and autocorrelation function analysis. Zones with a similar trend were thus defined within the study area to build up an idea of the variability over time of the whole study area.

  Descriptive statistics give us a preliminary quantitative idea of the global nature of the risk in each zone. The autocorrelation function measures the correlation of the risk value at various time intervals apart. This enables us to assess the risk dynamic and estimate its stability over time, i.e., how repetitive its pattern is.

  For each zone with a similar behaviour a specific model was built up following the methodology proposed by Box et al [12], based on the construction of a statistically suitable model that meets the succinct parameterisation principle (maximum structural simplicity and minimum number of parameters). This methodology is three phase: (1) Identification, (2) Estimation and Validation, and (3) Forecasting. In the first stage a study was made of the series' stationarity and seasonality and an identification was also made of the model's autoregressive and moving average terms. The model parameters were then calculated in the second stage and, in the third, a check was made of the

statistical validity of the estimates for the series analysed. Forecast assessment enables the error to be estimated, accepting or rejecting the estimated model and then returning to a new identification. In this study a model was initially proposed for each one of the previously defined zones; the next step was to group all the models with a common structure. The models were estimated using the time series 2000-2008, basing the forecast on 2009.

The statistical significance of the models was estimated by the Student's t test and the absence of residual autocorrelation was determined by Ljung–Box Q(k) tests. The model's forecast accuracy was estimated by means of Theil's U test[20].

Results

- *FPI Time Trend*

  Figure 1 shows the map of fuel models broken down by the fire propagation element, grass, undergrowth or leaf litter and also the localisation of selected pixels to explain the risk time trend from 2000 to 2009. Zone 1 corresponds to Mediterranean dryfarming land, mainly cereal, in which the propagating element is mainly the grass itself. Zone 2, lying in the Alpine region is occupied by conifer woods dominated by *Pinus silvestris* and firs, with leaf litter being the main fire propagation element. In northwest Navarre (Atlantic region) two zones were selected (3 and 4). Zone 3 is occupied by broadleaved beech woods. This type of wood is closed canopy with no undergrowth so the fire is propagated mainly by leaf litter. The predominant woodland type in zone 4 is broadleaved oak and chestnut. These woods are more open with undergrowth, which thus becomes the main fire propagation element.

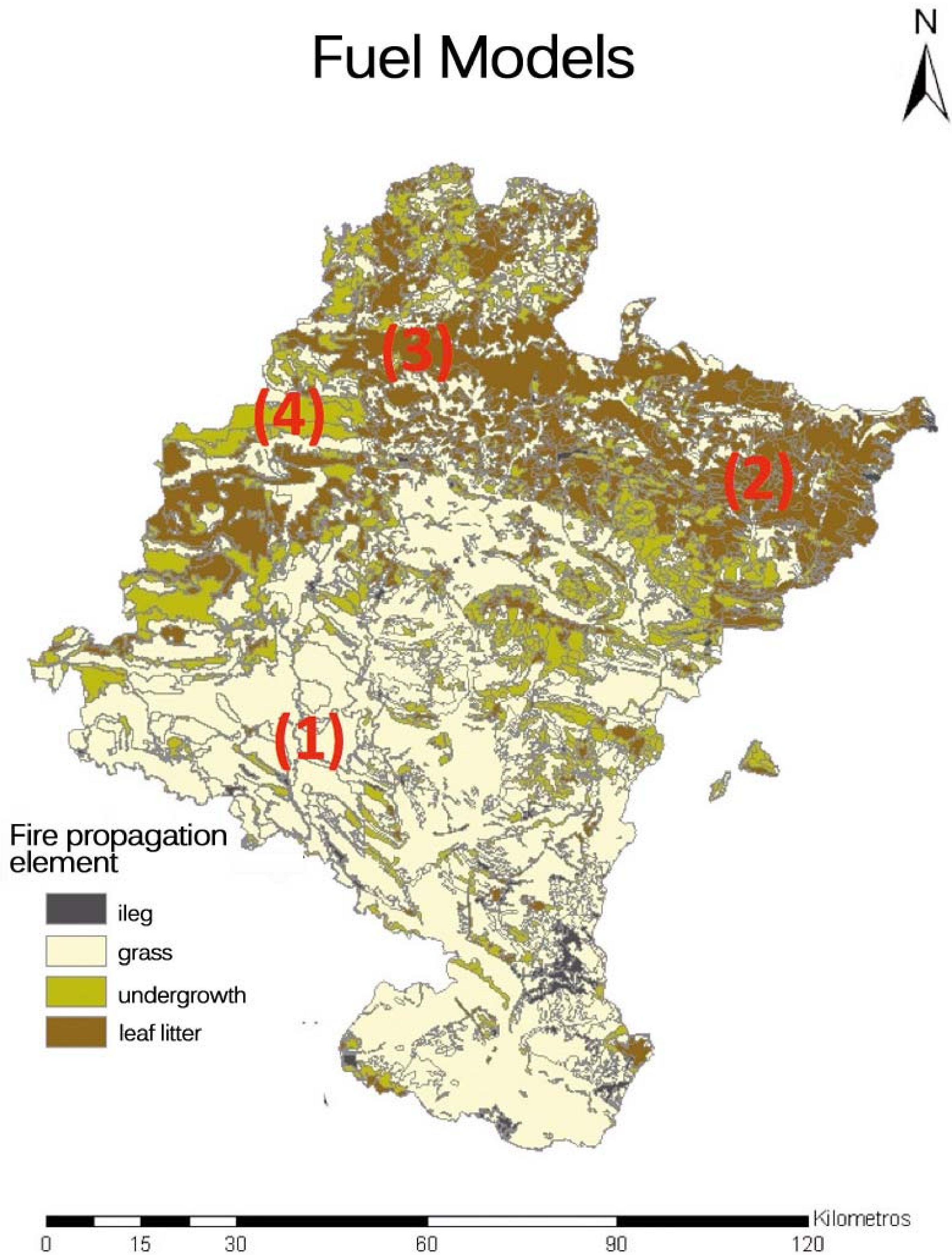


Figure 1. Fuel models grouped by the fire propagation element. The numbers in brackets refer to the four zones from which the time signatures of FPI_{NDVI} and FPI_{NDWI} have been extracted

(1) Mediterranean dryfarming land.
(2) Conifer woods in the Alpine region.
(3) Deciduous broadleaved woodland of the Atlantic region.
(4) Open deciduous broadleaved woodland with undergrowth of the Atlantic region.

Figure 2 shows the trend over time of FPI_{NDVI} and FPI_{NDWI} in the representative zones indicated in figure 1.

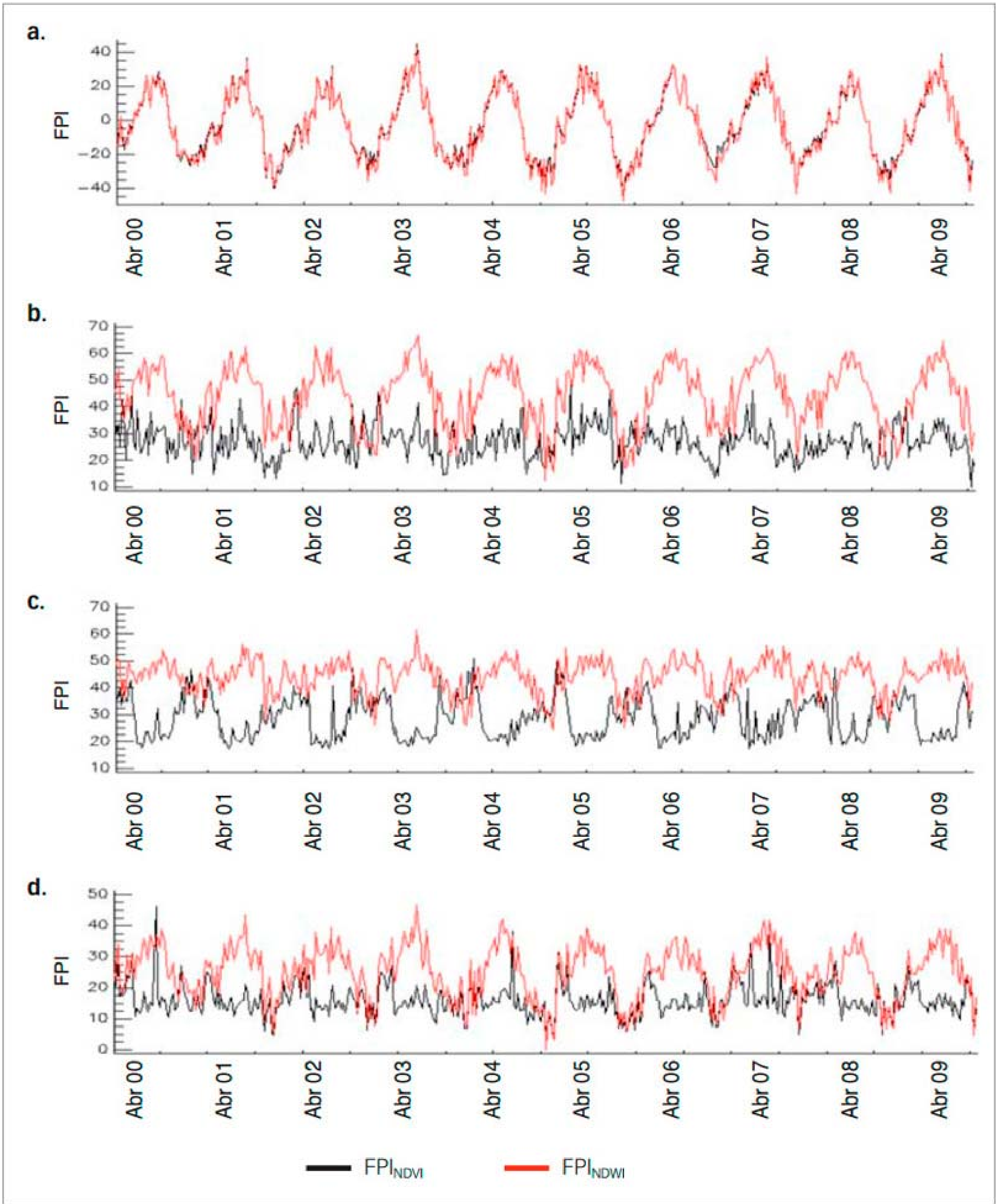


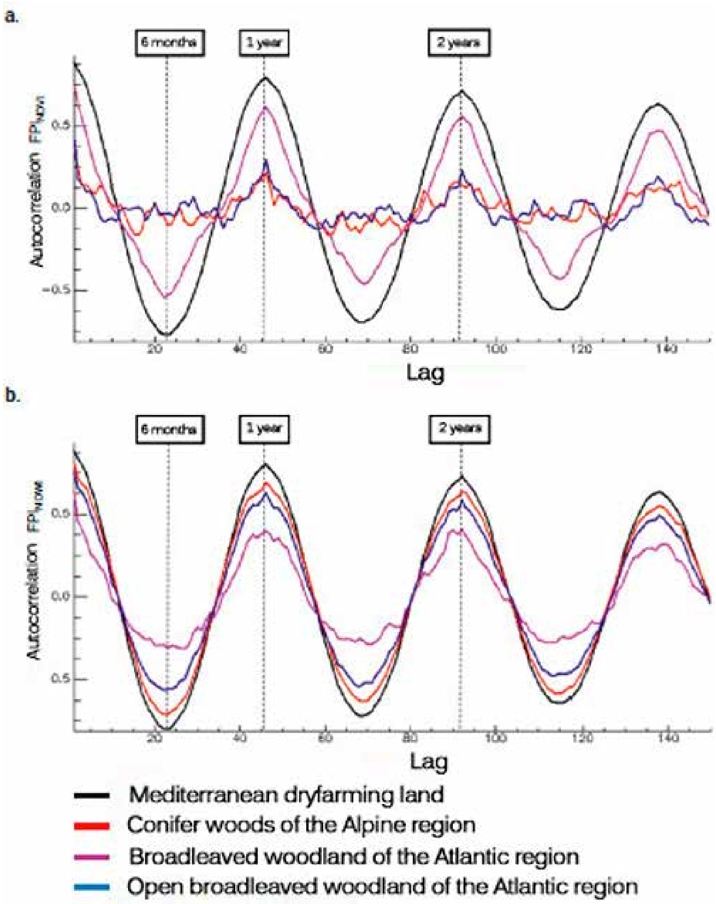
Figure 2. Risk trend calculated from the two indices in the four selected zones from 2000 to 2009. (a) Dryfarming land in the Mediterranean region. (b) Conifer woods in the Alpine region. (c) Broadleaved deciduous woodland of the Atlantic region. (d) Open broadleaved deciduous woodland with undergrowth in the Atlantic region.

THE FIRE POTENTIAL INDEX IS A DYNAMIC FIRE-RISK INDICATOR COMBINING INFORMATION ON FUEL TYPE, METEOROLOGICAL INFORMATION AND INFORMATION ON VEGETATION STATE FROM REMOTE SENSING IMAGES

In the herbaceous crops of the Mediterranean region (figure 2a) both indices show an almost identical risk behaviour. The risk shows a unimodal pattern with unmistakable summer peaks. In the woodland of the northern zone (figures 2b, 2c and 2d) the risk estimated from the FPI_{NDWI} is seen to be considerably higher than that estimated by the FPI_{NDVI} except in the winter, when the risk is lower. In the conifer woods of the Alpine zone (figure 2b) a more obvious annual pattern is shown by the FPI_{NDWI}. The FPI_{NDVI} shows a very irregular pattern. The broadleaved woods (figure 2c) show similar values for FPI_{NDWI} and FPI_{NDVI} during the winter and early spring but a very divergent trend in the summer, the risk rising with the FPI_{NDWI} and falling with the FPI_{NDVI}. In the autumn the values of

the two indices come back together. In the open deciduous broadleaved woodland with undergrowth (figure 2d) the behaviour is very similar in winter, spring and autumn. The summer behaviour, however, is divergent in values and trend, FPI_{NDWI} showing higher values than FPI_{NDVI}.

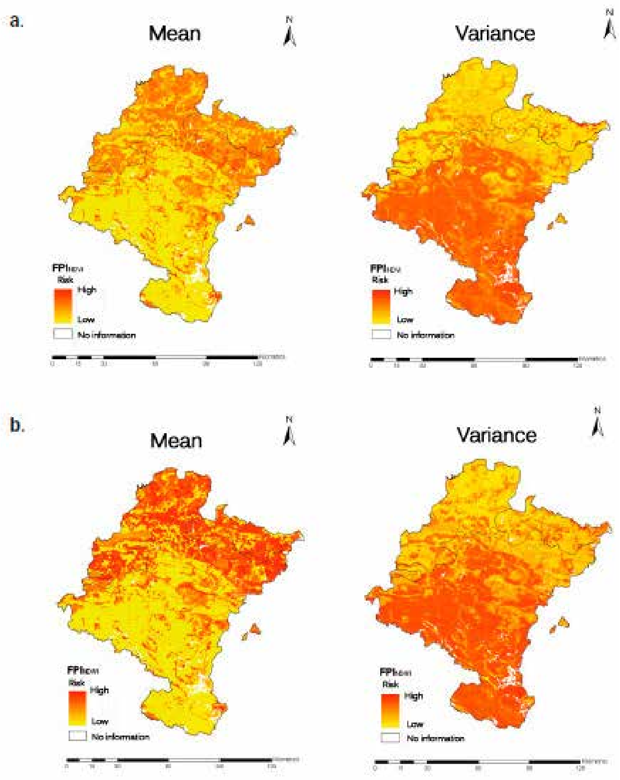
Figures 3a and 3b show the autocorrelation function up to 150 lags (a little over 3 years) calculated for the series of FPI_{NDVI} and FPI_{NDWI} in the selected zones (figure 1). These graphs show that autocorrelation is high in Mediterranean grassland and positive in the two indices in lag 1 (~8 days) and in lag 46 (~1 year) and very negative in lag 23 (~6 months). In the conifers of the Alpine zone the autocorrelation function of FPI_{NDWI} shows similar values to those of grass, while the autocorrelation values of FPI_{NDVI} are very low and irregular at all lags. The broadleaved woods of the Atlantic region with leaflitter propagation show slightly higher autocorrelation values for both indices. The broadleaved woods of the Atlantic region with undergrowth show a similar pattern to conifers in both indices.



Figures 3a y 3b. Autocorrelation up to 150 risk return periods calculated from FPI_{NDVI} (a) and FPI_{NDWI} (b) in the four selected zones from 2000 to 2009.

- *Zoning of the study area*

Figures 4a and 4b show the spatial distribution of the descriptive statistics (mean and variance) for FPI_{NDVI} and FPI_{NDWI} respectively; table 1 shows their mean values per fuel model. The leaflitter- or undergrowth-propagated fuel models show a higher mean and lower variance than grass propagated models.

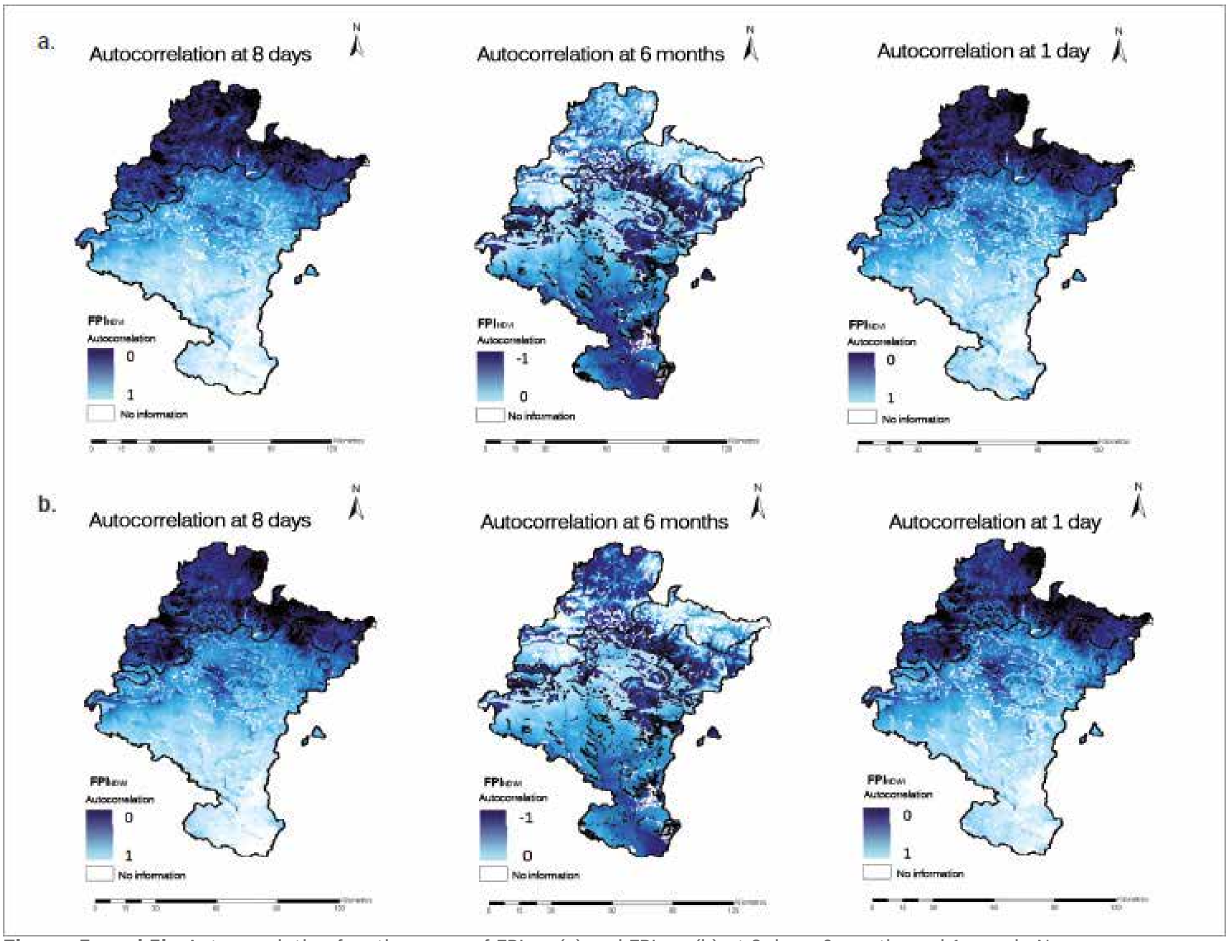


Figures 4a and 4b. Risk variance and mean maps estimated with FPI_{NDVI} (a) and FPI_{NDWI} (b) for the study period.

Table 1. Risk mean and variance estimated with FPINDVI and FPINDWI for each fuel model.

Fuel Model	FPI_{NDVI}		FPI_{NDWI}	
	Mean	Variance	Mean	Variance
1	-1.87	345.54	-2.64	397.86
2	6.59	207.94	7.58	256.42
3	27.04	37.81	38.26	50.03
4	21.78	37.81	28.51	121.22
5	18.14	67.17	25.51	122.55
6	29.30	74.48	38.99	88.76
7	40.78	110.19	56.93	23.94
8	29.48	52.06	44.29	63.37
9	28.79	64.54	39.32	68.57

Figures 5a and 5b shows the spatial distribution of the autocorrelation at 8 days, 6 months and 1 year for FPI_{NDVI} and FPI_{NDWI} respectively. There is a clear north-south gradient especially in the autocorrelations at 8 days and 1 year. The southern zone of Navarre shows higher and more positive values than the northern zone. In all cases the autocorrelation at 6 months is negative; in the north, however, the values are closer to zero.



Figures 5a and 5b. Autocorrelation function maps of FPI_{NDVI} (a) and FPI_{NDWI} (b) at 8 days, 6 months and 1 year in Navarre.

The result of these analyses (table 1 and figures 5a and 5b) show that the zones with similar statistics and autocorrelation functions at 8 days and 1 year correspond mainly to fuel types and bioclimatic zones. We therefore set up previous zoning based on the combination of these two variables and the presence of pure pixels within each class. The result was a 26-class «fuel type-bioclimatic region» zoning.

- *Construction of fire risk forecasting models*

A model for each class was built up from the zoning obtained in the previous section. This was based on the mean values of the time series corresponding to the pure pixels completely included in each zone.

THE SPACE-TIME COVERAGE OF SOME REMOTE SENSING SYSTEMS MAKES THEM ESPECIALLY SUITABLE AS INDICATORS OF THE VEGETATION STATE WITHIN THE RISK INDICES

The constructed models show a high statistical significance in the estimates of their coefficients, measured by student's t tests and also a high probability of absence of residual autocorrelation calculated from Ljung and Box Q(k) tests. For most of the estimated coefficients an absolute value student's t of over 2 was obtained. Ljung and Box Q(k) test values were low for all models for periods of half a year, one year and two years (23, 46 and 92 lags). The probability of rejecting residual autocorrelation in these models (information loss in explaining the model variable) for any lag is higher than 0.05 (barring 5 cases) and in some cases is higher than 0.8 (80%). This was then the criterion used for assessing the global model fit.

In a second stage the classes of the former phase were grouped in terms of the coincidence in the autoregressive model structure. Tables 2 and 3 show the new groups, their composition, significant lags of the selected autoregressive models and the forecasting accuracy estimated by Theil's U test for FPI_{NDVI} and FPI_{NDWI} respectively.

All the models show a structure with a very short term autoregressive parameter (1, 2 and 3 lags 8, 16 and 24 days) and another long term (45 and 46 lags c. 1 year). In all cases (except for the Atlantic chaparral-woodland), the model estimates a significant medium-term relationship (21, 22 and 23 lags c. 6 months) with a negative character and especially low values in the southern zone of Navarre. In the models including grass the system estimates a significant low-value and negative relation at 10 lags (c. 2.5 months).

IN THE MEDITERRANEAN REGION THE TWO INDICES SHOW AN ALMOST IDENTICAL BEHAVIOUR, WHILE IN THE ATLANTIC AND ALPINE REGIONS THE FPI_{NDWI} SEEMS TO GIVE A BETTER REFLECTION OF THE RISK IN SUMMER

Theil's *U* coefficient shows very low values in all models except for grass, although in the latter most of their value is built up in the covariance parameter, showing that the errors are random and proving the suitable forecasting accuracy of the models.

From the selected models the risk forecast has been drawn up for 2009 (46 dates) only of the FPI_{NDWI}, since this is the index that shows the best forecasting accuracy. Figure 6 shows the forecasts of FPI_{NDWI} for 2009 together with the calculated value. As can be seen the estimates replicate the actual risk pattern very closely, practically all the forecasts falling within the confidence interval.

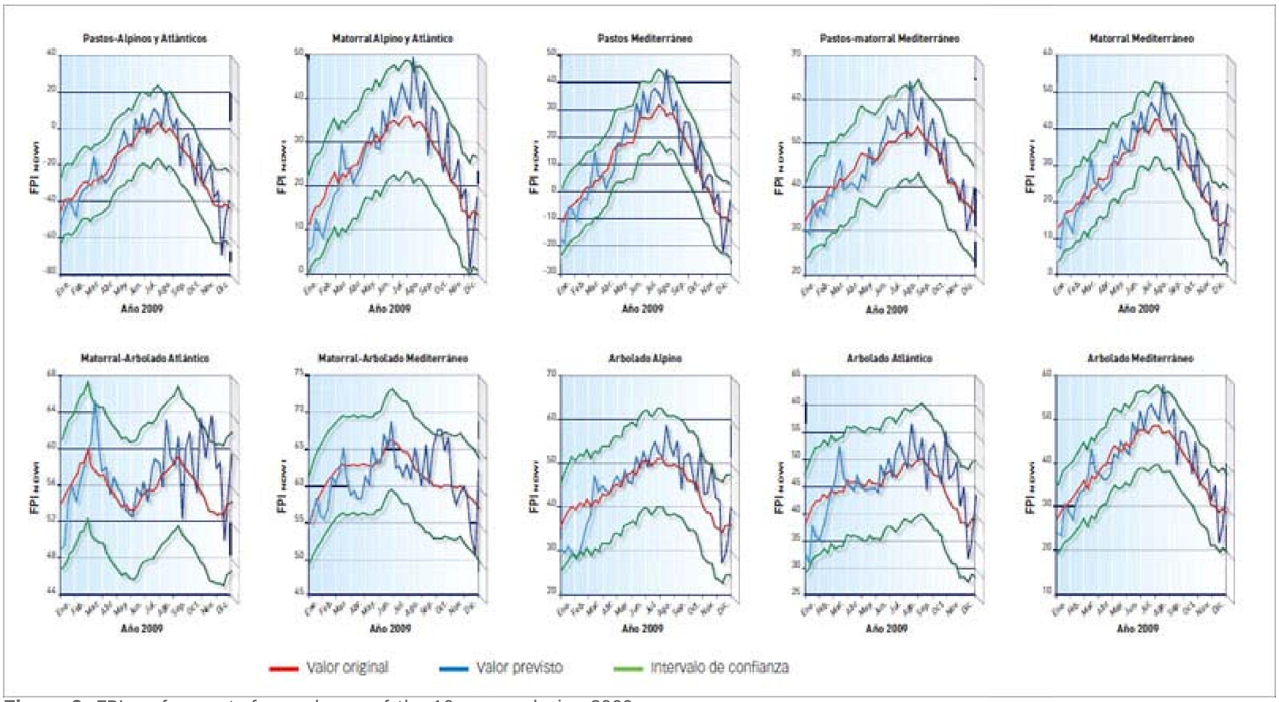


Figure 6. FPI_{NDWI} forecasts for each one of the 10 groups during 2009.

Discussion

FPI Time Trend

The similar behaviour of the two FPIs in herbaceous farmland of the Mediterranean region (figure 2a) is due to the fact that photosynthesis activity in these ecosystems is perfectly synchronised with the vegetation's moisture content. Thus, the pattern shown by the photosynthesis-related NDVI vegetation index and the moisture-related NDWI vegetation index is the same. The autocorrelation function (high and positive –figure 5a and 5b– in both indices in the short term and at one year) confirms a very marked annual cycle that tallies with the pattern of the Mediterranean region[1], for this is the predominant model in the zone.

The higher irregularity shown by the FPI_{NDVI} in conifer woods of the Alpine zone (figure 2b) is borne out by the autocorrelation function, which shows no significant values at any time lag. Moreover, the autocorrelation function of the FPI_{NDWI} shows significant short-, medium- and long-term autocorrelations, confirming the existence of an annual pattern. The difference between the two indices could be put down to the frequent presence of overcast skies in the area, even in summer. This introduces an information-distorting level of noise into the NDVI series, while the effect on the NDWI is less because it is calculated from longer, cloud-penetrating wavelengths.

THIS STUDY INTEGRATES TIME SERIES ANALYSIS INTO THE FIELDS OF REMOTE SENSING AND FIRE RESEARCH. THIS HAS UNEARTHED DYNAMIC RISK

In the broadleaved woods with leaflitter-propagated fires the autocorrelation function for the two indices shows a clear annual pattern with more significant values in the FPI_{NDVI} (figure 2c). The most important difference between the two occurs in summer, when the FPI_{NDVI} shows very low values and the FPI_{NDWI} peaks. This divergence is probably due to the fact that the NDVI is more photosynthesis dependent, responding very directly to phenological changes (very marked in

deciduous broadleaved woodland), reflecting itself in the higher absolute autocorrelation values. The summer leaf cover thus produces a very high live-load reading in the FPI_{NDVI}, and hence a very low estimate of the fuel likely to ignite. The more moisture-related NDWI, on the other hand, responds more directly to weather conditions and hence estimates a higher risk in summer, detecting as it does the leaves' water stress as the summer progresses.

Table 2. Selected models, structure and forecasting accuracy estimated by means of Theil's U coefficient for the index FPINDVI

Code Group	Description	Grouped models	Significant lags	Theil's Coefficient			
				U	P.skew	P.Variance	P.covariance
1	Alpine and Atlantic grass	AP1, AP2, AT1 y AT2	1, 3, 10, 22, 46	0,1938	0,0002	0,2433	0,7565
2	Alpine and Atlantic grass type 2	AP3, AT3	1, 2, 10, 22, 46	0,0733	0,0249	0,4658	0,5093
3	Mediterranean grass	M1 y M2	1, 2, 3, 10, 22, 46	0,2102	0,0684	0,2709	0,6607
4	Mediterranean grass-chaparral	M3	1, 2, 3, 6, 7, 11, 21, 46	0,0613	0,1388	0,3219	0,5393
5	Alpine and Atlantic chaparral,	AP4, AP5,AT4, AT5,	1, 2, 10, 23, 46	0,1409	0,0629	0,5778	0,3593
6	Mediterranean chaparral	M4, M5 y M6	1, 2, 3, 10, 21, 46	0,1132	0,1095	0,5388	0,3517
7	Alpine and Atlantic chaparral	AP6, AT6	1, 9, 27, 46	0,0778	0,0624	0,6069	0,3307
8	Atlantic chaparral-woodland	AT7	1, 2, 3, 11, 23, 45, 46	0,0624	0,0029	0,2154	0,7817
9	Mediterranean chaparral-woodland	M7	1, 2, 12, 21, 46	0,0464	0,0297	0,0074	0,9629
10	Alpine and Atlantic woodland	AP8, AP9, AT8 y AT9	1, 9, 23, 45, 46	0,0663	0,0001	0,2632	0,7367
11	Mediterranean woodland	M8 y M9	1, 3, 10, 21, 46	0,0707	0,1335	0,4865	0,3800

Table 3. Selected models, structure and forecasting accuracy estimated by means of Theil's U coefficient for the index FPINDWI.

Code Group	Description	Grouped models	Significant lags	Theil's Coefficient			
				U	P.skew	P.Variance	P.covariance
1	Alpine and Atlantic grass	AP1, AP2, AT1 y AT2	1, 3, 10, 21, 23, 34, 45,	0,1666	0,0246	0,2734	0,7020
2	Alpine and Atlantic chaparral	AP3, AP4, AP5, AP6, AT3, AT4, AT5, AT6	1, 3, 10, 21, 23, 34, 46	0,1065	0,0203	0,4752	0,5045
3	Mediterranean grass	M1 y M2	1, 3, 10, 21, 45, 46	0,1744	0,0699	0,3037	0,6264
4	Mediterranean grass-chaparral	M3	1, 2, 3, 10, 21, 46	0,0472	0,0257	0,3459	0,6284
5	Mediterranean chaparral	M4, M5 y M6	1, 3, 4, 10, 22, 42, 46	0,0833	0,0725	0,2865	0,6410

Code Group	Description	Grouped models	Significant lags	Theil's Coefficient			
				U	P.skew	P.Variance	P.covariance
6	Atlantic chaparral-woodland	AT7	1, 3, 10, 34, 42, 46	0,0327	0,1316	0,2185	0,6499
7	Mediterranean chaparral-woodland	M7	1, 3, 21,23, 46	0,0282	0,0090	0,1675	0,8235
8	Alpine woodland	AP8, AP9	1, 3, 22, 42, 46	0,0629	0,0032	0,3416	0,6551
9	Atlantic woodland	AT8 y AT9	1, 3, 16, 22, 34, 42, 46	0,0500	0,0247	0,3445	0,6308
10	Mediterranean woodland	M8 y M9	1, 3, 10, 21, 23, 46	0,0500	0,0416	0,2990	0,6594

In the open broadleaved deciduous woods with undergrowth (figure 2d) the autocorrelation function shows a clear pattern in the FPI_{NDWI} index, while FPI_{NDVI} shows no significant autocorrelations at any time lag. In this ecosystem the phenological cycle captured by the vegetation indices is the result of the admixture of the evergreen woods with undergrowth and the deciduous trees. This is reflected in a great irregularity throughout the year, especially when using the FPI_{NDVI}, heavily dependent on the phenological cycle. This is clearly shown in the autocorrelation function. Nonetheless, the FPI_{NDVI} series does show a reduction of the risk in spring, when the foliage begins to grow, albeit less marked that the deciduous woods without undergrowth. The same effect is seen in winter when the verdure of the undergrowth brings down the FPI_{NDVI} values as compared with the previous ecosystem because it detects a higher load of live vegetation, undergrowth. Moreover the FPI_{NDWI} follows a similar pattern as in the previous ecosystem, estimating the highest risk values in summer.

THE RISK HAS BEEN MODELLED AND FORECAST FROM A SINGLE TYPE OF MODEL, THE AUTOREGRESSIVE MODEL. THIS SIMPLIFIES THE FORECASTING PROCEDURE, FOR THE RISK DEPENDS ONLY ON ITS OWN HISTORY

The results of the spatial analysis of the basic statistics and the autocorrelations at 8 days, 6 months and one year validate a preliminary zoning based on the bioclimatic zone and fuel model. The fuel models show very different means and variances, indicating different risk levels and variability throughout the year. The autocorrelation function, for its part, shows a different pattern from one bioclimatic region to another, indicating a very different stability of the risk pattern. For example the better autocorrelation at 1 year in the Mediterranean zone is probably due to the fact that the summer drought is very regular and constant, thereby conferring stability on the risk. In the north, on the other hand, cooler and more humid, the water limitation is not an annual constant so the risk pattern varies more from year to year. On the basis of these results we have drawn up a specific preliminary model for each «fuel model-bioclimatic region» combination. In all cases the proposed models are autoregressive, modelling the variable in terms solely of the past. The main differences between them lie in their structure (necessary risk-modelling lags). In a second phase the models sharing the same structure were pooled and forecasts were made only for the FPI_{NDWI} in view of its better forecasting accuracy. The 26 original classes were grouped in 10 for this index. The pure Atlantic and Alpine grassland show a similar behaviour so they have been pooled into one class. The two tree fuel models (8 and 9) were also pooled, while maintaining the distinction between bioclimatic zones. The chaparral with various levels of association with grassland and Atlantic and Alpine woodland has been grouped, except for the Atlantic chaparral-woodland, which had to be modelled separately. In the Mediterranean region chaparral was broken down into three classes according to its association with grassland or trees.

All these models share a common structure with an autoregressive parameter in the very short term and another in the long term. This shows that the risk value depends largely on its value in the recent past and shows a similar behaviour to the previous year on these same dates. The significant negative medium-term relation found (except in the Atlantic chaparral-woodland), can be explained by the bearing of the spring's risk on the autumn's risk. Wet springs generate a lot of biomass and ipso facto a higher risk in late summer and autumn. The significant negative low value at 2.5 months found in the models with grassland among the fuel might be due to the fact that this model captures a dynamic risk relation associated with the short-term vegetative trend of some fuels, such as some grassland ecosystems.

Conclusions

In this study the fire risk has been modelled on the basis of two indices: the FPI_{NDVI} and the FPI_{NDWI}. In the Mediterranean region both indices show an almost identical behaviour whereas in the Atlantic and Alpine regions the FPI_{NDWI} seems to give a more faithful reflection of summer risk, probably because it is more related to moisture than photosynthesis. This index also shows a better forecasting accuracy.

The study shows that the fuel type-bioclimatic region combination engenders classes with a characteristic risk behaviour. It has also been possible to model and forecast the risk with a single model type, the autoregressive. This simplifies the forecasting procedure because the risk depends only on its own history without taking auxiliary variables into account.

This study has integrated time series analysis into remote sensing and fire research. This is a groundbreaking and original approach. In our opinion the results suggest that this methodology has a great potential in fire research and management. These methodologies can also be easily extrapolated to other environmental contexts.

ACKNOWLEDGEMENTS

This work has been funded by a FUNDACIÓN MAPFRE research grant..

BY WAY OF A GLOSSARY

FPI: Fire Potential Index.
FPI_{NDWI}: Fire Potential Index alculado con el índice NDWI.
FPI_{NDVI}: Fire Potential Index calculado con el índice**NDVI.**
NDVI: Normalized Difference Vegetation Index.
NDWI: Normalized Vegetation Water Index.
AST: Análisis estadístico de series temporales
AR: Modelo autorregresivo.
MA: Modelo media-móvil.
ARMA: Modelo autorregresivo y media-móvil.
ARIMA: Modelo autorregresivo y media-móvil con término de integración.
MODIS: MODerate resolution Imaging Spectroradiometer.
ρ_r: Reflectancia en el canal rojo.
ρ_{nir}: Reflectancia en el canal infrarrojo cercano.
ρ_{swir}: Reflectancia en el canal SWIR 1.
T_{max}: Temperatura máxima.
H_{rel}: Humedad relativa mínima.
H: Altitud.
$Hcm_{10hrfrac:}$ Humedad del combustible fino y muerto.
Cv_{cor}: Carga de combustible susceptible de arder.

TO FIND OUT MORE

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SEGURIDAD y Medio Ambiente

Year 32 N125 First Quarter 2012

FUNDACIÓN MAPFRE

Environmental Legislation in vehicle repair

Environment

Vehicle repair shops have introduced many changes into their working habits to bring them into line with the applicable environmental legislation. As a result their general image has improved. This progress is a reflection of the sector's obvious effort to adapt to a scattered range of legal requirements that are pooled together and analysed in this article.

Repair shops have to demonstrate their qualification by applying the best environmental techniques

By **RAQUEL ADANERO BEJERANO.**

What is the environmental impact of a vehicle repair shop? To carry out its repairs the workshop or garage concerned has to take from the environment – directly or indirectly – a series of resources that it then uses and transforms. Finally, the waste products that are no longer useful are discharged back into the environment. Analysing and understanding these activities and their environmental impact makes it easier in turn to understand the whys and wherefores of the legal requirements. (table 1)

Tabla 1. Repercusiones ambientales de la actividad de los talleres.

The environmental aspects are the necessary inputs and the outputs back into the environment. These are the main targets of the environmental legislation due to their interaction with the environment and the potential damage they might cause.

Environmental legislation applicable to the sector

The range of environmental legislation is so large and varied that it is sometimes difficult to decide which actions should be taken to comply with its requirements. The applicable legislation, broken down by the aspects it refers to, may be checked in the websites of the Ministry of Agriculture, Food and the Environment (*Ministerio de Agricultura, Alimentación y Medio Ambiente*) and the regional authorities (*comunidades autónomas*) as well as the requisites incumbent on the sector.

General Obligations. Environmental Permit

Several permits or licences have to be obtained from the local council for running a vehicle repair shop. One of them is the environmental permit. This lays down the compulsory environmental protection measures, depending on the type of activity and the particular firm's production capacity. These measures have to be complied with before going ahead with the activity and then adhered to throughout the whole licence period.

Waste generation and management

Vehicle repair generates a great amount of waste: scrap metal, tyres, paint, used oil, etc. Due to its sheer volume and hazardousness it needs to be dealt with properly.

The Contaminated Soil and Waste Act 22/2011 of 28 July (*Ley de residuos y suelos contaminados*) lays down the obligations to be met by the workshop as initial waste producer or possessor. The workshop can deal with this waste in three basic ways: firstly, in its own right, secondly, by hiring the services of a registered firm or thirdly by handing it over to a public or private waste collection entity. Whichever option is chosen, the workshop is bound to furnish the local environmental authority with proof of the correct management of the non-hazardous commercial waste or opt into any existing public waste management system. The local byelaw indicates how domestic waste is to be handed over.

Normally this involves hiring the services of waste managers and participating voluntarily in integrated management systems (IMS). Before hiring the services of authorised waste transporters and handlers in each *comunidad autónoma*, the workshop has to find out about each one and the waste they deal with. This information can be culled from the environment websites of the *comunidades autónomas*, section: environmental quality. The IMSs also require previous authorisation from the *comunidades autónomas* where they are set up. There are IMSs for handling used oil, end-of-life tyres, containers, batteries and accumulators, lamps, electrical and electronic equipment, etc. The workshop is bound to observe all the conditions and procedures laid down by these systems (table 2).

Table 2. Hazardous workshop waste

- Lamps containing mercury.
- Button fuel cells.
- Windscreen-cleaning fluid.
- Inactivated Airbags.
- Activated carbon of paint spray booths.
- Oil/water separator sludge.
- Aerosols.
- Used oil and vehicle oil filters.
- Batteries.
- Antifreeze.
- Brake fluid.
- Diesel and petrol filters.
- Part-cleaning solvents.
- Time-expired paint products.
- Paint equipment cleaning solvents.
- Air conditioning gas.
- Brake pads containing asbestos.
- Solvent recycling sludge.
- Remains of used paint.
- Paint-impregnated spray-booth filters.
- Paint-impregnated plastic and masking tape.
- Sanding dust.
- Absorbents impregnated with paint oil or other hazardous waste.
- Recipients that have contained waste or hazardous substances.

Administrative procedures of the waste producer

Before going ahead with its activities the workshop has to report its intention to the competent body of its *comunidad autónoma*. This requisite is applicable to all hazardous waste producers and also those producing over 1000 tons a year of non-hazardous waste. This communication will contain the information laid down in annex VIII of Ley 22/2011 and the workshop concerned will then be entered in the «Waste handling and production register» that each *comunidad autónoma* is bound to keep up to date.

Proper waste labelling

THE ENVIRONMENTAL PERMIT LAYS DOWN THE ENVIRONMENTAL PROTECTION MEASURES TO SUIT THE FIRM'S PARTICULAR ACTIVITY AND OUTPUT

Ley 22/2011 cancels the previous obligation of drawing up an annual report of waste generated by the producers of hazardous waste but maintains the obligation of a four-yearly waste-minimisation study, barring those workshops classed as small producers. A workshop is eligible for classification as a small producer of hazardous waste if the annual amount generated does not exceed 10,000 kg. The application for inclusion as such can be made in the «Register of small waste producers».

Management of hazardous waste

Hazardous waste is any residue that might affect human health, the environment or safety. It has to be dealt with according to RD (Royal Decree) 833/88 and RD 952/97, insofar as these royal decrees do not conflict with the provisions of *Ley 22/2011*.

As well as the necessary administrative procedures for hazardous waste producers – barring those classed as small producers – the workshop is bound to furnish a financial guarantee to cover liabilities that might arise from its waste-generating activities.

The owner is bound to separate, label and store the hazardous waste and also to keep all documents that vouch for its proper management.

Waste separation avoids mixtures that might increase their hazardousness or hinder subsequent management. The containers and seals therefore have to be in perfect condition, resistant to the particular contents and not liable to form dangerous combinations therewith. These containers will bear a visible label measuring at least 10 x 10 cm; this label will clearly, legibly and indelibly indicate all the following: the container contents, waste identification code, the nature of the risks posed (pictograms and/or R phrases, set risk phrases specifying the nature of the risks of the chemical substances and hazardous preparations), the packaging date and the name, address and telephone number of the waste owner.

A hazardous waste storage zone has to be set up, observing the maximum storage times. *Ley 22/2011* lays down the following times: six months for hazardous waste (the competent authority of the *comunidades autónomas* will be entitled to amend this time on justified grounds, guaranteeing the protection of human health and the environment); one year for non-hazardous waste that is to be eliminated and two years for non-hazardous waste that is to be reclaimed, i.e. converted into raw materials or energy.

LEY 22/2011 LAYS DOWN THE OBLIGATION OF PRESENTING A HAZARDOUS WASTE MINIMISATION STUDY EVERY FOUR YEARS

These deadlines run from the depositing of the waste in the storage facility. To guarantee environmental safety conditions, even though the legislation does not indicate specific obligations, the hazardous waste storage facility has to be sited outdoors (or, if indoors, in a well-ventilated site well away from any heat sources), with a waterproof floor, protection from rain and fitted with spill retention systems to deal with any accidental container breakage.

For the handling of hazardous waste there is a series of protocols laying down the proper internal control and management procedures; the corresponding documents must be kept for at least five years. These documents record acceptance of each item of hazardous waste, transfer notifications, control and monitoring documents (or hazardous waste delivery notes for small producers) and register of the waste handed over.

Particular legislation in relation to hazardous waste and substances

As well as the general waste law and the development regulations there is a whole range of legislation that might affect vehicle repair shops depending on the substances they handle and the type of waste they produce.

Prevention of air pollution

The vehicle repair activity generates mainly different types of air pollutants: combustion gases from heating boilers, paint spray booths, engines, etc., and emissions deriving from the painting of vehicles and the use of solvents in general, etc.

Ley 34/2007 is the basic law for the prevention of air pollution. It lays down the catalogue of potentially air-polluting activities (CAPCA in Spanish initials), since updated by RD 100/2011, which also establishes the basic provisions for applying the law.

The workshop is bound to check this catalogue to find out which group it belongs to in terms of its polluting potential. The most polluting sites belong to group A, with stricter requisites than for groups B or o C. Section 060102 comprises the activity «renewal of vehicle finishes», together with classification thresholds depending on their solvent consumption capacity (s.c.c). Another activity with s.c.c. is the cleaning of parts in mechanical workshops (table 3).

Table 3. Section of the catalogue of potentially air-polluting activities (RD 100/2011)

Renewal of vehicle finishes	Group	Code
s.c.c > 200 t/year or 150 kg/h	A	06 01 02 01
s.c.c ≤ 200 t/ year or 150 kg/h and > 0.5 t/year	---	06 01 02 03
s.c.c ≤ 0.5 t/year	---	06 01 02 04

Table 4. Section of the catalogue of potentially air-polluting activities (RD 100/2011)

Activity	Group	Code
Burners of RTI >= 300 MWt	A	03 01 01 00
a.s.a.. of RTI < 300 MWt and >= 50 MWt	A	03 01 02 00
a.s.a.. of RTI < 50 MWt and > 20 MWt	B	03 01 03 01
a.s.a.. of RTI <= 20 MWt and > 2.3 MWt(1)	B	03 01 03 02
a.s.a.. of RTI <= 2.3 MWt and >= 70 kWt (1)	C	03 01 03 03
a.s.a.. of RTI. < 70 kWt	-	03 01 03 04
Other furnaces without contact between combustion gases and heated material not specified elsewhere with RTI > 2.3 MWt	B	03 02 05 09
a.s.a.. of RTI <= 2.3 MWt and >70 kWtt	C(2)	03 02 05 10
Drying and granulation equipment or the like, or heating equipment with direct contact with combustion gases, not specified elsewhere, with a rated thermal input => 20 MWt	A	03 03 26 34
RTI => 2.3 MWt and < 20 MWt	B(2)	03 03 26 35
RTI => 70 kWt and < 2.3 MWt	C(2)	03 03 26 36
RTI < 70 kWt	-(2)	03 03 26 37

(2) If hazardous substances are being used or the activity is carried out at less than 500 m from any of the areas listed below, the activities belonging to group B will be considered to form part of group A; those belonging to group C will be considered to form part of group B and the activities without a group will form part of group C on the criterion of the competent body of the comunidad autónoma. The areas concerned are built-up areas; protected nature sites, including peripheral zones with some sort of protection; areas belonging to Red Natura 2000, and areas protected under international instruments. a.s.a: activities specified above

As regards combustion gases, the key criterion is the rated thermal input (RTI) of the burners of the painting booths. If the workshop has heating boilers and other boilers these also have their own coding (section 0301, combustion boilers, gas turbines, engines and others) (table 4).

The *comunidades autónomas* are entitled to establish criteria for potentially polluting activities, changing them to more restrictive groups, depending on the air-quality improvement plans they might put into place.

Obligations of the tenure holders of catalogued activities
The tenure holders of activities are in general bound to minimise emissions by applying available technical improvements.

> *A VEHICLE REPAIR SHOP IS ELIGIBLE FOR CLASSIFICATION AS A SMALL PRODUCER OF HAZARDOUS WASTE IF IT GENERATES LESS THAN 10,000 KILOGRAMS A YEAR*

Workshops catalogued in groups A or B are subject to administrative authorisation by the comunidad autónoma; those of group C are bound to send notification up to the comunidad autónoma in such form and terms as might be laid down by the latter.

The authorisation granted to the facilities of groups A and B establishes the necessary controls and emission limits to be met under current legislation. These authorisations are granted for a maximum term of eight years. For those belonging to group C the competent regional authority might lay down post-notification control requisites to suit each particular case.

Workshop guide for environmental legislation compliance

Initial procedures and general obligations.

- Find out the state of the soil before starting the activity.
- Apply to the council for the environmental permit.
- Selection of the necessary waste handlers (web check) and application for the acceptance documents of each type of waste.
- Reporting the waste production to the environmental body of the *comunidad autonoma* before going ahead with the activity.
- Application for entry in the register of small producers if eligible.
- Furnishing of the financial guarantee covering such liabilities as might arise from its activities, except for those workshops classed as small producers.
- Select a separate place for storing waste, duly separating off the hazardous waste.
- Prepare the hazardous waste store (outdoors or a well-ventilated indoor site, protected from the rain with a spill retention system).
- Fit out the area for the reception and temporary storage of end-of-life vehicles. It will be fitted with impermeable flooring, spill collection facility, oil-water separation plant and water treatment equipment.
- Check the rated thermal input of the burners of paint spray booths.
- Calculate the plant's solvent consumption capacity.
- Check the catalogue of potentially air-polluting activities and ascertain which group the workshop belongs to.
- Apply for the administrative authorisation from the competent body of the *comunidad autonoma* (groups A and B) or make the notification thereto (Group C), according to the group it belongs to.
- Obtain the discharge authorisation from the competent local or regional authority, depending on which runs the collection system, or from the competent hydraulic authority if not discharged into a sludge collection system.
- Draw up a preliminary soil report and send it up to the competent body of the *comunidad autonoma*.

Periodical and Particular Obligations

Waste Management

- Separate waste into independent containers, according to type.
- Label the containers as indicated in the regulations.
- Abide by the waste storage deadlines.
- Hand over the waste to transporters and handlers authorised by the *comunidad autonoma*.
- Record waste deliveries in documents: prior notification of transfer, control and monitoring documents and recording of deliveries made.
- Keep waste management documents available (entry in the small producer register, acceptance documents, transfer notifications, control and monitoring documents, registry of withdrawals).
- Present the waste-minimisation study every four years, except for those classed as small producers.

Elimination and management of equipment containing pyralene

- Annual declaration of equipment included in the PCB phase-out inventory (content of polychlorinated biphenyl, PCB, polychlorinated terphenyls and appliances containing 1 dm3 or more of same.

- Labelling of equipment included in the PCB phase-out inventory and of the doors of the premises if the PCB volume is higher than 5 dm_3.
- Marking of equipment that has been decontaminated and of equipment whose concentration has been reduced by the changes made.
- Obligation of having chemical analyses of PCB-containing or -contaminating equipment conducted by certified bodies and reporting of the results to the competent bodies of the comunidades autonomas. Inclusion of the results in the annual possession document.
- Decontamination or elimination of equipment with a PCB content equal to or higher than 50 parts per million (ppm) and electricity transformers with concentrations higher than 500 ppm. Deadline: 1 January 2011.
- Decontaminate or eliminate, through an authorised handler, equipment containing less than 1 dm_3 of PCB at the end of its useful life.
- Equipment or appliances that might contain PCB and show fluid leaks have to be eliminated or decontaminated as soon as possible and the event reported to the *comunidad autonoma*.

Prevention of soil contamination

- Send up to the competent body of the *comunidad autonoma* such periodical reports as may be asked for.
- Carry out such soil-decontamination activities as may be required by the competent body of the *comunidad autonoma*.

Prevention of air pollution

- Control and monitor emissions as established by the competent body of the *comunidad autonoma* in the authorisation procedure, applicable legislation or air quality plans.
- Keep up to date the activity's air-emission register and maintain it for at least ten years.
- Report recorded information using such methods as may be established.

Handling of vehicle refrigerant gases

- Ensure that persons handling coolant systems with fluorinated refrigerants in vehicles have the necessary personal qualification for doing so.
- Reuse the refrigerant. Recover the R12 in specific bottles and hand it over to the hazardous waste handler; also the R134a as from 31/12/2012.
- Return the containers of these refrigerants to the distributor or hand them over to the authorised hazardous waste handler.
- Check for leaks and repair any that might be detected, before refilling the system with gas.
- As from 01/01/2011 not to top up vehicles with R134 or fit out old vehicles for using same.
- Not to purchase non-rechargeable containers unless manufactured before 04/07/2007.

Noise abatement and prevention of vibration

- Check the noise emission limits laid down in local byelaws.
- Have the required periodical measurements carried out by accredited control bodies.

Wastewater management

- Obtain discharge authorisation and abide by the stipulations laid down therein.
- Observe the requirements of the discharge authorisation and keep it up to date.
- Pay the established discharge fee.
- Comply with such prohibitions as may be established on the discharging of certain substances.
- Measure the quality of discharged water with the required frequency, doing so through a credited control body.

Workshops are therefore bound to conduct such controls as may be laid down in the authorisation or communication of the *comunidad autónoma* and in legislation as well as such requirements as may be phased in by air quality plans approved at the various government levels. RD 100/2011 brings in a new feature here: for facilities with environmental management systems certified externally, by EMAS or ISO 14001, the comunidades autónomas will be entitled to simplify the mechanisms for checking compliance with their obligations.

THE WORKSHOP HAS TO CHECK THE CAPCA TO FIND OUT WHICH

The facilities included in groups A, B and C are bound to keep an up-to-date registry recording the activity's emissions, including the data of each emitting

GROUP IT BELONGS TO IN TERMS OF ITS POLLUTING POTENTIAL

source and the functioning thereof. This information has to be kept for at least ten years and reported to the competent body of the *comunidad autonoma* following the established method for that purpose.

Fluorinated gases and ozone-depleting substances

The corresponding legislation is applicable to workshops and technical personnel that work with vehicle air-conditioning systems with fluorinated gas refrigerants such as R134a or ozone depleting substances like R12; this legislation lays down obligations for the certification of personnel that install, maintain or check these systems; including the control of leaks, recharging and recovery of fluorinated refrigerants and the handling of the gas containers of vehicle air-conditioning systems using fluorinated refrigerant gases.

As a general rule all attempts should be made to reuse the refrigerant unless it contains chlorofluorocarbons, CFCs, such as R12; all contaminated refrigerants that cannot be reused have to be handed over to a registered hazardous waste handler.

Prevention of noise, vibration and odour pollution

The main sources of noise and vibration are compressors, paint spray booths, running engines and working pneumatic tools and also bodywork repair operations. Odour emission stems from the products used.

Local byelaws flesh out the stipulations laid down by the *comunidad autónoma* on applicable noise limits. Applicable limits and monitoring frequency will depend on the location of the workshop and the time of day at which the activity is carried out. In terms of measurements the workshop is bound to hire the services of an accredited control body.

Elimination of wastewater

Water pollution, in a properly fitted-out and operating workshop, stems mainly from vehicle washing and cleansing of the plant and equipment; this produces a small run-off of oil and dirt in general, plus remnants of detergents, etc.

Water legislation is laid down in *Real Decreto* (Royal Decree) 1/2001 of 20 July, approving the revised text of the *Ley de Aguas* (Water Act). This establishes the need of possessing discharge authorisation, applying limits to substances that are hazardous to air quality and establishing the payment of a discharge control fee.

The discharge authorisation comprises discharge control information, information on how it is to be carried out, necessary treatment plant, operation control items, quantitative and qualitative limits on the composition of the discharge and the amount of the discharge control fee. The maximum term is five years, successively renewable thereafter if the quality standards and targets are met at each moment.

When the discharges affect the sewerage network or collection systems run by local or regional authorities (or delegated bodies), the authorisation is granted by the competent local or regional body; otherwise it is the competent hydraulic authority that grants the discharge authorisation.

A chamber needs to be set up for taking water samples. The applicable pollutant limits might be laid down in the discharge authorisation, but the normal reference is the applicable legislation, such as the local byelaws when discharge is made into the sewerage network.

Prevention of soil contamination

Workshop soil contamination might result from accidental spills of substances like oil and other pollutant vehicle fluids; this risk can be avoided by following good working practices.

The soil polluting potential of vehicle repair workshops is dealt with in annex I of Real Decreto 9/2005, dealing with potentially soil polluting activities; this royal decree imposes two main obligations on the activity tenure holders: reporting the state of the soil to the *comunidad autónoma* and decontaminating it if it is declared to be contaminated.

THE WORKSHOP HAS TO CHECK THE CAPCA TO FIND OUT WHICH GROUP IT BELONGS TO IN TERMS OF ITS POLLUTING POTENTIAL

RD 09/2005 establishes the deadline of February 2007 for reporting the preliminary soil condition to the *comunidad autónoma*. Once this initial report has been examined, the tenure holder might be asked for further details, analyses or additional reports to assess the degree of soil contamination. With the coming into force of Ley 22/2011, the tenure holder will be bound to send in periodically to the *comunidad autónoma* the reports containing the base information for the declaration of contaminated soil.

When the soil is declared to be contaminated there is then an obligation to carry out the necessary activities for its environmental recovery and cleansing, in such terms and deadlines as may be dictated by the competent body of the respective *comunidad autónoma*. This obligation falls on the polluters; if there are several, the following will be held

accountable on a several and subsidiary basis in this order: the owners of the contaminated soil and its possessors. The *Real Decreto* also establishes publicity procedures for the soil on which a potentially polluting activity has been carried out and, above all, soil that has actually been polluted. Any definitive closure of the plant or cessation of the activity triggers the soil-quality declaration procedure.

Liability for compliance with environmental legislation

BREACHING THE ENVIRONMENTAL LAW MIGHT LEAD TO CIVIL, PENAL AND ENVIRONMENTAL LIABILITIES

Apart from legal compliance consideration also has to be given to the liability the workshop might incur in if it does not observe the legal precepts. Much of the aforementioned legislation includes information on the established administrative penalties for any breach. The defaulting tenure holder's liability is not limited to these penalties; depending on the damage caused and its consequences, the breach might also give rise to civil, penal and environmental liabilities.

Table 5. Penalties (article 47 of *Ley 22/2011*).

Tipo de infracción	Fine	Other penalties
Slight	Non-hazardous: Up to €900	
	Hazardous: Up to €9000	
Serious	Non-hazardous: 901 to €45,000	Struck off for less than one year
	Hazardous: 9001 to €300,000	Revocation or suspension of the authorisation for up to one year
Very serious	Non-hazardous: €45,001 to 1,750,000	Hazardous: €300,001 to 1,750,000
	Struck off for between one and ten years.	Temporary or definitive closure, total or partial, of the facilities or plant for a maximum term of five years.

Legislation Annex

Waste management legislation

- **Ley 22/2011**, de 28 de julio, de residuos y suelos contaminados.
- **RD 833/88** Reglamento sobre la gestion de residuos peligrosos.
- **RD 952/97**, amending Reglamento 833/88.
- **Orden MAM 304/2002** Lista europea de residuos.

Additional National Waste Legislation

- **RD 679/2006**, de 2 de junio, que regula la gestion de los aceites usados.
- **RD 379/2001**, de 6 de abril, que aprueba el Reglamento de almacenamiento de productos quimicos y sus instrucciones tecnicas complementarias MIE APQ-1, MIE APQ-2, MIE APQ-3, MIE APQ-4, MIE APQ-5, MIE APQ-6 y MIE APQ-7.
- **RD 1383/2002**, de 20 de diciembre, sobre gestion de los vehiculos al final de su vida util.
- **RD 1378/1999**, de 27 de agosto, que establece medidas para la eliminacion y gestion de los policlorobifenilos, policloroterifenilos y los aparatos que los contengan. Modificado por RD 228/2006, de 24 de febrero, que establecen las medidas para su eliminacion y gestion.

Fluorinated gases and ozone-depleting substances

- Regulation (EC) No 1005/2009 of the European Parliament and of the Council of 16 September 2009 on substances that deplete the ozone layer.
- Real Decreto 795/2010, de 16 de junio, por el que se regula la comercializacion y manipulacion de gases fluorados y equipos basados en los mismos, asi como la certificacion de los profesionales que los utilizan.
- Directive 2006/40/EC of the European Parliament and of the Council of 17 May 2006 relating to emissions from air conditioning systems in motor vehicles.

Legislation on the prevention of air pollution

- Ley 34/2007, de 15 de noviembre, sobre calidad del aire y proteccion de la atmosfera.

- RD 100/2011 Catalogo de actividades potencialmente contaminadoras de la atmosfera.

Noise Abatement Legislation

- Ley 37/2003, de 17 de noviembre, del ruido.
- RD 1513/2005 Evaluacion y gestion del ruido ambiental
- RD 1367/2007 Zonificacion acustica, objetivos de calidad y emisiones acusticas.

Legislation on the discharge of industrial wastewater

- **RDL 1/2001** Ley de aguas
  Discharge aspects: Basic water law.
- RD 849/1986 RDPH RDPH
  Discharge aspects: Develops the water law (old) in terms of discharges.
- **Orden MAM/1873/2004**
  Discharge aspects: Instructions and official forms for declaring discharges and applying for authorisation.

Legislation on the prevention of soil pollution

- **RD 09/2005**, de 14 de enero, por el que se establece la relacion de actividades potencialmente contaminantes del suelo y los criterios y estandares para la declaracion de suelos contaminados.
- **Ley 22/2011**, de 28 de julio, de residuos y suelos contaminados.

SEGURIDAD y Medio Ambiente
Year 32 N125 First Quarter 2012
FUNDACIÓN MAPFRE

Energy Optimisation and Catalytic Degradation of plastic waste

Environment

The demand-driven surge in the production of low biodegradable plastic material is generating a huge build-up of plastic waste and a concomitant environmental problem. An efficient way of solving this problem is the development of catalysts capable of optimising the plastic burning process. This catalytic degradation might also drive molecular cracking processes to generate specific compounds of high added value.
This study sets out to analyse a series of zeolite catalysts (particularly a laboratory synthesised nano-sized catalyst and another of natural origin) that reduce the degradation temperature of polyethylene while also selectively generating compounds with a high commercial demand. The results show that nano-sized catalysts outperform naturally occurring micro zeolites.
The conclusion drawn from this study is that by controlling the properties of the zeolite catalyst it is possible to cut down the energy needed for the thermal degradation of polyethylenes and thus optimise the cracking of the polymer chain in a controlled way, generating gaseous compounds of a high added value

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Plastic's excellent properties and low cost have generated a constantly growing demand in recent decades, unparalleled in other traditional materials[1]. The annual growth in Europe and South America is reckoned to be between 4 and 8%[2]. This soaring demand has been led by polyolefins, such as polyethylene (PE) or polypropylene (PP), on the strength of their growing range of applications, ousting many other kinds of material. This versatility has made polyolefins today's most important polymers in the plastics industry, accounting for 60% of the total plastics marketed[1]. The worldwide PE output is now nearly 90 million tonnes, representing 34% of the market[3]. Europe's average per capita consumption of plastics is estimated to be 100 kilograms adding up to a total yearly consumption of 40 million tons[4,5]. This huge consumption leads to a proportional surge in the amount of plastic waste; due to its low biodegradability, moreover, this waste is becoming a severe environmental problem. For example, Europe consumed 40 million tons of plastic material in 2000, translating into 30 million tons of waste[6].

Plastic waste, much more bulky than traditional organic waste, now occupies a large volume of landfill sites or rubbish tips. About 62% of Europe's waste ends up in these tips[5]. This situation, however, has led to increasing public concern and there is a growing legislative-environmental lobby, like those who advocate a 35% reduction in this type of waste by 2020[7]. Furthermore, the costs of this process, which generates explosive and toxic gases, have increased. One of the first measures taken to try to reduce this glut of plastic waste was energy recycling or direct incineration to generate energy. In Europe 23% of the original waste is now used in this way[5]. Nonetheless this type of recycling also comes in for much

criticism because of the generation of toxic gases, together with the fact that the energy released is often not properly harnessed. It also calls for a high operating temperature and produces a wide range of products that have a very low economic value.

THE USE OF SOLID CATALYSTS SOLVES SEVERAL PROBLEMS IN THE THERMAL DEGRADATION OF PLASTIC WASTE

Mechanical recycling, for its part, involving the melting down and remoulding of the thermoplastic waste to form a new product, is generally welcomed by society. Unfortunately, this type of recycled material is of very poor quality due to the degradation reactions during the recycling process, the varying nature and quality of the plastic waste and the presence of additives and impurities in the original plastic. All these factors greatly limit its use possibilities[8]. Moreover, this recycled product is often even more expensive than the virgin material[7]. In the United Kingdom only 17% of plastic waste is mechanically recycled; the rest is dumped in landfill sites or incinerated[7].

Given the complications in the traditional plastic-waste reduction procedures, a technology has recently been developed based on the transformation of plastic waste into high added value hydrocarbons that can serve as chemical products and/or fuel. An initial approach is based on controlled thermal degradation, albeit with the limitation that the required temperature ranges from 500 to 800ºC and the resulting products have high molecular weights and are of an uneven consistency. The thermal degradation of polymers into material of low molecular weight, on the other hand, has the drawback of producing a wide range of waste[2]. Furthermore, the reactions are highly endothermic and hence call for a high energy input[9]. In view of all these snags the use of solid catalysts seems to be a promising approach to solving these problems. In particular the reaction temperature is considerably lower (between 350 and 550ºC), reducing the energy consumption of the process[6,10]. Using this method it is also possible to control the fraction of products and cut down the distribution thereof, making materials of higher added value[11].

The catalysts most commonly used for optimising the thermal degradation process are porous solid acid catalysts such as amorphous silica alumina, ordered mesoporous material and zeolites[8], the latter being the most studied catalysts. Zeolites are porous crystalline aluminosilicate compositions (natural or synthetic) with a very defined structure formed by tetrahedral units of $SiO4$ or $AlO4$ connected by oxygen bridges, generating a network of canals, cavities and micropores of a very precise molecular size. Due to these properties and its inherent acidity, zeolite is the main component in the industrial catalysts used in the catalytic cracking of crude oil to produce gasoline.

Catalytic cracking applied to the breakdown of polyolefins has focused mainly on polymer transformation into gaseous and liquid products of interest. In the case of PE, for example it has been reported that the mesoporous material Al-MCM-41 produces hydrocarbons within the gasoline fraction while ZSM-5 directs the cracking towards light compounds with a large production of gaseous and aromatic hydrocarbons[8]. When using Al-MCM-41 as a catalyst the cracking occurs by a mechanism of random scission due to its large pore size and medium acidity. The zeolite HZSM-5, on the other hand, leads to an end-chain cracking pathway due to its small pore size and strong acidity[8]. The catalyst's particle size has been proven to be important; this was confirmed by analysing nanocrystalline zeolite ZSM-5 samples, which show a high cracking activity due to their large external surface and low diffusional constraints[8]. Similar results have been found by studying beta zeolites, where it has been shown that the particles with the smallest crystal size (~ 100 nm) give the best performance due to the bigger surface area and higher production of liquid compounds[12].

Despite the abovementioned evidence, there is still a need for further study of different zeolite catalysts in the degradation of polyolefins. In particular the effect of nano-sized catalysts on the temperature and catalytic degradation of plastics is a variable that has been little studied as yet, despite its promising industrial potential. Furthermore, given the environmental impact of these technologies, there is now a pressing need for studies into the use of natural catalysts to cheapen the implementation of this vital technology. The objective of this article is therefore precisely to study the effect of zeolite catalysts on the degradation of plastic waste. The study will focus in particular on the effect of particle size and acidity on the degradation temperature and breakdown products. A general scheme of the idea behind our research, i.e., the chemical recycling of plastic waste, is shown in figure 1.

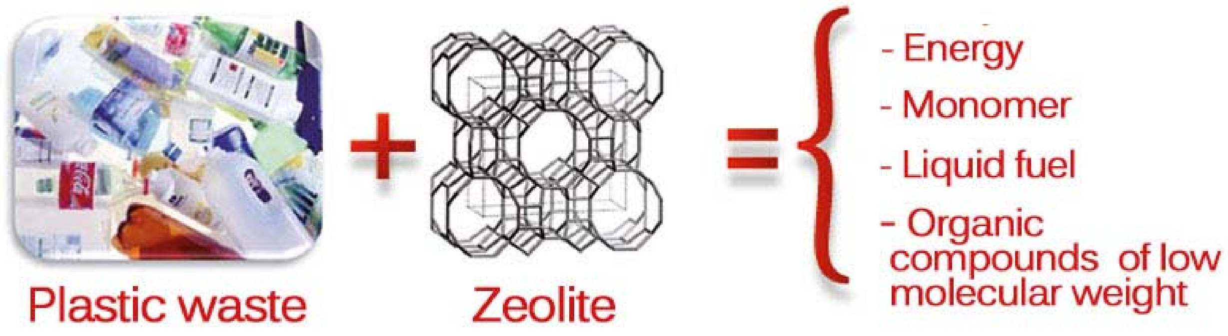

Figure 1. General scheme of the chemical recycling of plastic waste using zeolite catalysts

Materials and Methodology

Preparation of acid zeolites

Natural zeolite (Nat) was subjected to an ionic exchange with a solution of HCl to obtain its protonated form (H-Nat). The exchange with lanthanum was achieved by bringing the H-Nat into contact with a solution of La(NO3)3, obtaining La-H-Nat. The nano-sized zeolite studied is a ZSM-2 (NZeo), obtained using the following molar composition 0.53Li2O:0.5Al2O3:6TMAOH:3.4SiO2:315H2O, in due accordance with previous reports[13]. This zeolite has a pore diameter (pd) of 7.4 Å. Like the natural zeolite it was then protonated (H-NZeo) and modified with lanthanum (La-H-NZeo). Micrographs from electron microscopy show the mean particle size to be 100 nm.

Degradation Test

The PE catalytic degradation was carried out in a Pyrex semibatch reactor, which was heated by a thermal cracking reactor with programmable controller. A defined amount of the PE was then mixed with the catalyst inside the reactor. The system was heated up to 400, 450 or 500° C in steps of about 6°C/min under a nitrogen flow; it was then left to react for 40 minutes once the study temperature had been reached. The gaseous products were captured in gas collection bags and the liquids were retrieved in a cold trap and NaCl (-20º C), and then weighed. The collected gases were analysed by gas chromatography.

The gaseous fraction was analysed by gas chromatography (Perkin Elmer Clarus 500) fitted with a Flame Ionisation Detector (FID) and a Capillary Column HP-Plot/Al2O3 (Agilent), to determine the presence and concentration of different hydrocarbons (C1-C6). A packed column (Supelco 60/80 Carboxen 1000) was also used in line with a thermal conductivity detector (TCD) for analysing the amount of CO2.

The PE used in the study is linear with a mean molecular weight of 120,000 g/mol; it was synthesised in our laboratory using a metallocene catalyst Et(Ind)2ZrCl2 in presence of the co-catalyst methylaluminoxane in concentrations of 3.5 x 106 mol of catalyst, Al/Zr ratio of 3000, 2 bar and 60º C. The thermogravimetric analyses (TGA) were conducted in a Netzsch TG 209 F1 Iris under a nitrogen environment with a flow of 25 ml/min from room temperature up to 600º C at a heating rate of 20º C/min. For each experiment 4.7 mg of polymer (<120 mesh) was mixed with the desired amount of catalyst (typically 2 mg, 30% of the total mass).

Results

Optimisation of thermal degradation

Table 1 gives a summary of the catalysts studied and their respective chemical modifications. Note that the nano-sized zeolite (~100 nm) without any type of modification shows a high acidity in comparison, for example, with natural zeolite. On the other hand the modifications made with protons and lanthanum are effective in terms of increasing catalyst acidity, especially that of the natural catalyst, boosting it by more than one order of magnitude. Note also that, although the pure nano-sized catalyst shows a high acidity in comparison with the natural catalyst, the latter obtains the highest acidity once modified.

Table 1. Main characteristics of the various zeolites studied

Catalyst	Eº (mV)	Total number of acid sites [μeq m^{-2}]
NZeo	200	1.7
H-NZeo	318	1.9
La-H-NZeo	310	1.8

Catalyst	E° (mV)	Total number of acid sites [μeq m^-2]
Nat	40	1.7
H-Nat	400	1.5
La-H-Nat	500	1.4

When the polymer is thermally degraded with no type of catalyst, its temperature of maximum degradation (Tmax) is 492.5º C. When the degradation occurs in presence of the nano-sized catalyst, however, the Tmax drops right down to 418.7º C. Not only Tmax falls but also the initial degradation temperature. Examples of the curves obtained by thermogravimetry are shown in figure 2. In particular it shows the results for the pure polymer and for the polymer in presence of the various nanocatalysts.

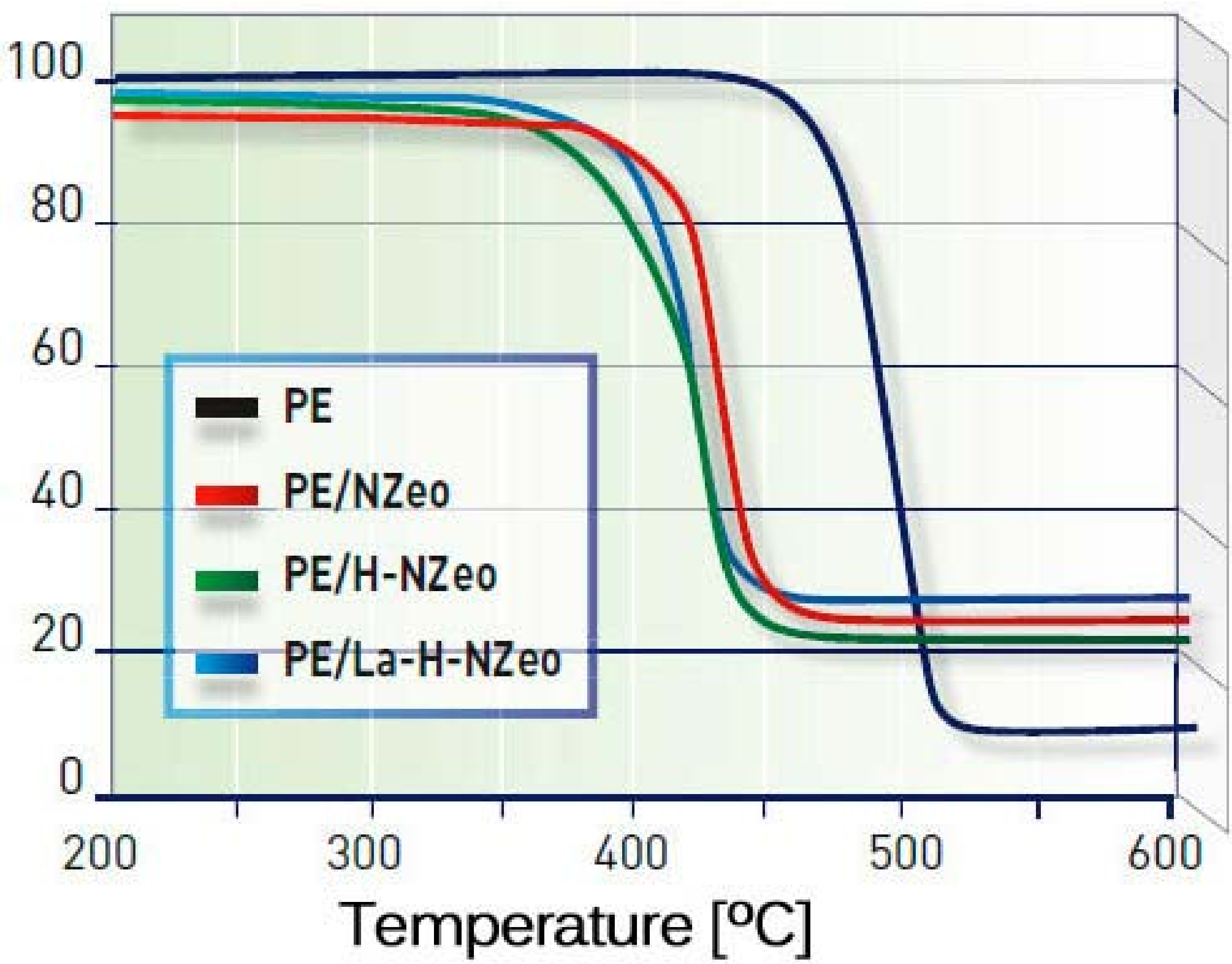

Figure 2. Thermogravimetric analysis of the pure polymer in presence of different nanocatalysts.

Table 2 sums up the effect of the type of particle and its acidity on Tmax. It also shows the Tmax without a catalyst. This table shows the marked effect of catalyst acidity and crystal size. Natural zeolite without modification has no significant degradation effect due to its low acidity. As the modification-induced acidity increases, however, Tmax is brought down by over 50º C. These results show the strong impact of catalyst acidity on the degradation process. Nonetheless our results also show that catalyst size is another important variable. This is brought out by a comparison of the Nzeo catalyst with NatZeo. The modified natural particle show a considerably higher acidity than the nano-sized particle but the latter brings about the bigger Tmax fall. This confirms that the smaller catalysts, ipso facto with a larger surface area, act more efficiently on the polymer degradation process.

Table 2. Effect of the type of catalyst on the polyethylene degradation temperature. Tmax: temperature of maximum weight loss in a TGA test

Catalyst	T_{max} [ºC]
N/A	492.5

Catalyst	T_{max} [ºC]
NZeo	428.2
H-NZeo	422.3
La-H-NZeo	418.7
Nat	490.2
H-Nat	446.2
La-H-Nat	444.0

A direct consequence of the marked fall in degradation temperatures (table 2) is that the necessary thermal degradation temperature in a reactor might be up to 70º C lower than that necessary in direct pyrolysis. As pointed out in the introduction to this study, therefore, the use of catalysts of this type made cut down the necessary energy input for thermally breaking down polymers.

Breakdown Products

Table 3 sums up the effect of the catalyst on the breakdown products. In particular it shows the percentage in weight of the (gaseous) volatile compounds with respect to liquids of a higher molecular weight. This table confirms that the type of particle and its acidity not only modify the degradation temperature but also the breakdown products. In particular, the nano-sized zeolite produces the largest amount of gaseous compounds, and the higher the acidity the higher is the catalytic activity for producing volatile compounds. Additionally, chromatographic column analysis, revealing the composition of the gaseous products, showed that these catalysts are highly selective towards propylene (~ 70%) and propane (~ 15%). This shows that the use of zeolite catalysts promotes selectivity towards specific products of high added value.

Table 3. Effect of the type of catalyst on the breakdown products. Reaction temperature: 450º C

Catalyst	% volatile compounds	% liquids	% solids and wax
N/A	47	51.1	2
NZeo	83	14.8	2
H-NZeo	87	10.7	2
La-H-NZeo	91	7.5	2
Nat	38.1	13.2	48.7
H-Nat	49.1	23.2	27.7
La-H-Nat	63.4	11.8	24.8

Discussion

The results of this work shed light on the two most important variables in the catalytic degradation of plastic waste: particle size and acidity. In particular, the effect of nanocatalysts on the catalytic degradation of plastic waste has been little studied hitherto, even though it has a very promising potential. The use of nano-sized zeolites with a bigger pore size (pd=7.4 Å for ZSM-2) than the nano-sized ZSM-5 zeolite (pd~ 5.5 Å) considerably improves the efficiency of the process, as shown in this study. This effect is reflected in the degradation temperatures, which are brought down most by nano-sized catalysts. Nonetheless, our results show that the acidity is not the only parameter controlling this process since the catalyst with the highest acidity does not achieve the highest activity. Although the two catalysts studied herein both brought down the degradation temperature and hence reduced the necessary energy input, the larger specific area of NZeo makes it more active.

The effect of the nano-sized structure is borne out by analysing the breakdown compounds. In the scientific literature on this subject it is difficult to find volatile compound productivities higher than 80% w/w[14,15,16,17] , even in other nano-sized catalysts. In our case, however, the Nzeo-based catalysts achieve a 90% gas proportion. This result shows that the crystal size and catalyst pore diameter, together with acidity and crystal structure, could control the production of gaseous compounds, as in the case of the particle NZeo[18]. This is confirmed by analysing the natural zeolite; although it has a higher acidity than NZeo, it produces a lower amount of gaseous compounds. Even the catalyst La-H-Nat, with higher acidity, cannot match the gaseous compound content of NZeo.

Our results show the complexity of these systems, since different reactions simultaneously vie with each other, and each has its own kinetic behaviour depending on the properties of each catalyst. In particular, competition between thermal pyrolysis and the catalytic cracking sought in the system may mean that certain deposition or chain growth reactions are favoured to build up heavy or light compounds according to the catalyst's specific area or acidity[15,19]. The high production of gaseous compounds in the zeolites studied herein, especially NZeo, is due to the overcracking that occurs in very acidic environments[17]. The initial cracking fragments may hence spread through the catalyst's pores and continue reacting in these cavities, producing more gaseous compounds [15,21]. Thus, a catalyst with a larger specific area, such as the nano-sized particles, may perform this process better. This model is confirmed by analysing the lower amount of gases produced by natural micro-sized zeolite in comparison with the nano-sized catalyst, even though both have similar pore sizes (pd ~ 7.4 Å for NatZeo). The reduction of secondary reactions in the zeolite particles, due to the steric limitations associated with their small pore size, explains the formation of larger hydrocarbons. Further alkene reaction is thus inhibited; this explains the selectivity of these systems in favour of the formation of propylene and other alkene molecules[16]. Note also that other variables such as pore size may cause other nano-sized zeolite particles (e.g. beta) to generate mainly liquid compounds, as recently reported[12].

Conclusions

Our results show that the use of zeolites is a viable method for optimising the polyethylene degradation process. By modifying the characteristics of the zeolite, in particular the particle size and acidity, it is possible to control the degradation reactions. The nano-sized zeolites achieve a bigger degradation-temperature fall and a larger production of gaseous compounds than natural zeolites. This higher catalytic activity is explained by the larger specific external surface area of the nano-sized compounds, favouring the surface cracking process. Moreover, by means of acidic modifications, the natural zeolites can perform as well as polyethylene degradation facilitators; together with their low price this makes their use commercially feasible in industrial applications. The use of these catalysts could therefore be applied at industrial level to cut down the energy input of the plastic waste degradation process, while at the same time generating volatile compounds of high commercial value, such as propylene.

ACKNOWLEDGEMENTS

The authors with to thank FUNDACIÓN MAPFRE and Dr. Raúl Quijada for their support while carrying out this research.

TO FIND OUT MORE

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