Introduction of threat analysis into the land-use planning process

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ABSTRACT

The subject of this paper is a method for introducing risk assessment into the land-use planning (LUP) process. Due to adaptations of the results of risk assessment, which are needed to make the risk assessment usable by land-use planners, we term the overall process threat analysis. The key features of the threat analysis can be summarised as follows. (i) It consists of three main steps. The first is determination of the threat intensity level of an accident, the second is analysis of the environmental vulnerability of the surroundings of an accident, and the third, integrating the previous two, is determination of a threat index in the accident impact zone. All three are presented in GIS based maps, since this is a common expression in LUP. (ii) It can and should be applied in the early stages of the LUP process. The methodology is illustrated by an example in the context of renewal of a land-use plan for the Municipality of Koper in Slovenia. The approach of threat analysis follows directions of the Article 12 of the Directive 96/82/EC of the European Commission (the Seveso II Directive).

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1. Introduction

The most effective preventive approach for reducing the consequences of industrial accidents is provision of appropriate distances between hazardous installations and residential areas [1–4]. Proper distances should be assured by means of land-use planning (LUP): consideration of risk assessment results in land-use planning for the purpose of limiting the consequences of accidents is one of the requirements of the Seveso II Directive [5,6]. EU member states are searching for their own best ways of achieving compliance with this specific requirement [4,7–13], but the process seems to be slower than expected at the time of adopting the Directive.

In general there exist three approaches to risk-informed land-use planning: the approach of generic separation distances, a risk-based and a consequence-based approach [3].

The determination and use of "*generic*" separation distances is based on the type of activity rather than on a detailed analysis of the risks. These safety distances are usually derived from expert judgments and are mainly based on historical factors, experience, rough consequence calculations or information regarding the environmental impact of the plant. The approach of generic separation distances has been established and used in Germany and Sweden [2,3].

The risk-based approach focuses on the assessment of both consequences and expected occurrence frequency or probability of possible accident scenarios. The results are represented as individual risk and/or societal risk (expressed as individual risk contours and societal risk (F–N) curves) [3,14–16]. LUP criteria are based on specific acceptability criteria with respect to the calculated risk. In terms of LUP the results of risk analysis are used as a basis for risk reduction measures in terms of lowering both the probability and the magnitude of incidents, as well as a guideline for determining the acceptability of proposed development in the vicinity of hazardous sites. This approach is used in the United Kingdom and in the Netherlands [13,17–20].

The consequence-based approach focuses on the assessment of the consequences of a number of reference scenarios obtained from a quantitative risk assessment (QRA) study. Damage threshold values for accident physical effects (overpressure, thermal radiation, toxic concentration) are determined with respect to undesired consequences (fatalities, irreversible effects, reversible effects, etc.) [3]. The method has generally been used in Finland, Luxembourg, Spain, Belgium and Austria [2,10,13,21,22]. France has also been included as a typical example of the consequence-based approach until recently [2,3]. After the Toulouse accident and the French Law for Land-Use Planning of 2003, the approach has changed into a hybrid one, requiring the operator and the authorities to take the likelihood of accident scenarios into account [23,24]. Besides introducing a probabilistic approach into the risk assessment process, the novelty/new feature is consideration of probabilities in the framework of strategies for communication with local communities, with the aim of

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achieving consent for existing situations or development proposals.

A hybrid approach combining risk and consequence based approach has also been devised and used in Italy [13]. The method requires the identification of four damage zones. Threshold values for each of the three accidental cases (toxic concentrations, fire and explosion) are supported by legislation. The vulnerability of surrounding land uses is also taken into consideration [25,26]. The frequency values calculated for each scenario are considered as worsening factors for LUP restrictions and are not used to express the individual and societal risk.

EU member states expected a resolution of the land-use planning issues by providing common guidelines for land-use planning, as required by the Seveso II Directive; these were prepared by the Institute for systems informatics and safety and the Major Accident Hazard Bureau (MAHB) of the EU Joint Research Centre in Ispra, respectively [27,28]. The guidelines are aimed at assisting the interpretation of the requirements of the Article 12 of the Seveso II Directive as a help in achieving compliance. An additional aim is to provide collaboration between land-use planners and risk assessment experts [28]. However, since no specific or detailed support is provided in these guidelines in terms of integrating risk assessment results into the land-use planning process, it remains to be seen what their practical utility and benefit will be, especially because member states will need to develop their own practice on this subject.

The approaches discussed above are either procedures involving evaluation of the conformity assessment of existing urbanisation with selected risk criteria (ex-post evaluation), or are applied during the licensing process for new developments (ex-ante evaluation). In both cases a land-use plan is already available, so risk assessment is not involved in the plan preparation process; it is, rather, a basis for compliance assessment with the plan. The LUP issues in this regard are presented schematically in Fig. 1. The figure also shows the ultimate aim of the threat analysis for solving the risk related LUP issues.

Part (a) of Fig. 1 illustrates current situations: 10 or 20 years after the plan approval, and due to urbanisation development in the surroundings of the industrial zone where a Seveso II plant is situated, the situation is no longer satisfactory or acceptable (high risk) as it was at the time of plan adoption (at $t = 0$). Possible LUP safety (risk) improvement measures are: relocation or shut down of the Seveso II plant; movement of the population from the residential objects in proximity to the plant if the risk situation is extreme; implementation of additional preventive measures at the plant (e.g. safety improvement by installing additional safety device) as well as more effective protective measures in the surroundings (e.g. additional technical barriers against direct exposure of the population or improvement of the external emergency plan by assuring
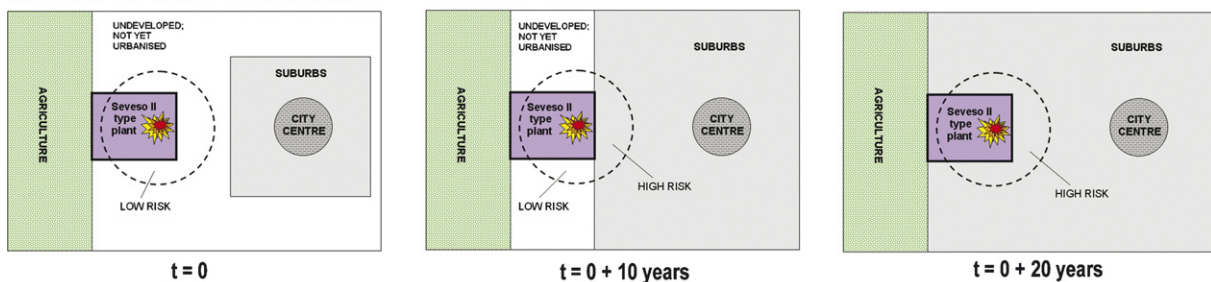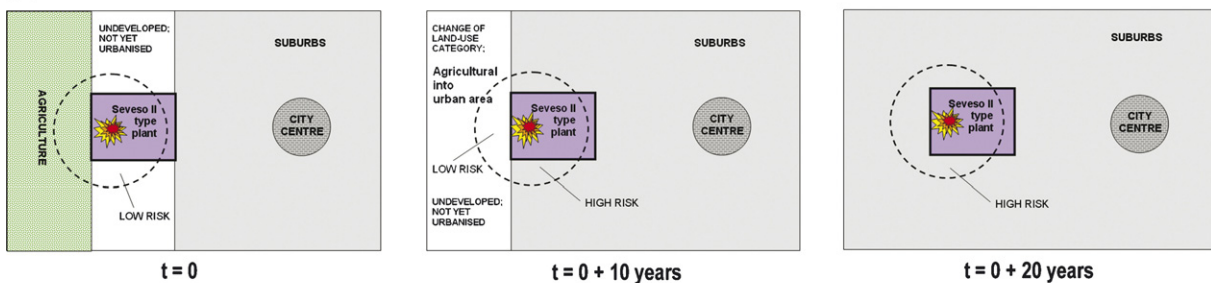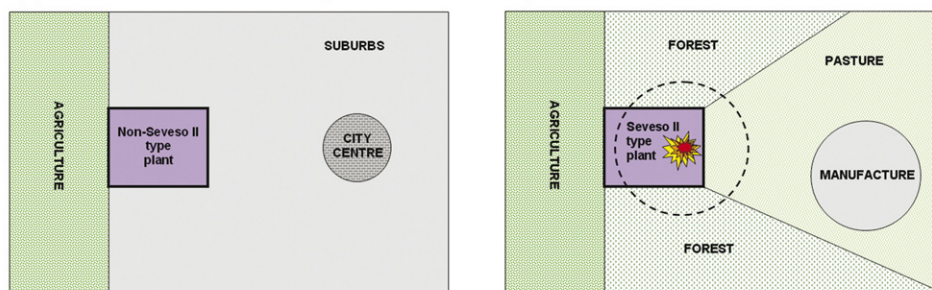

Fig. 1. Illustration of risk related LUP issues.

effective evacuation). Part (b) of Fig. 1 illustrates how the conformity assessment is to be understood. Such an assessment at $t=0$, i.e. at the time of adopting a plan may show that the situation in terms of risk is acceptable (low risk). However, if the conformity assessment is done again after 10 or 20 years, the result may no longer be satisfactory or acceptable. This would mean that only the "frozen" land-use state, as shown at $t=0$, assures conformity and low risk. If such a "freezing" of the current state of a land-use plan would indeed be applied it would fundamentally change the existing philosophy and practice of land-use planning. It would basically countermand what the plan (the society) was initially saying should happen as land-use development in the future, so a question about the very purpose of the land-use planning would arise. Part (c) of Fig. 1 illustrates the aims of threat analysis for ensuring either that no Seveso II plants are allocated in industrial zones surrounded by urban or other vulnerable areas (e.g. surface and groundwater for drinking purposes, natural protected areas, etc.), or that specific and clear conditions for siting hazardous installations are provided in the initial stages of preparing a land-use plan, so that risk conflicts are avoided during the whole timeframe of implementing the plan.

Description and the illustration of the threat analysis are provided in the following sections using the example of renewal of a land-use plan for the Municipality of Koper, Slovenia. The Seveso II plant is an LPG loading/unloading and storage facility.

For the purpose of this article the selected terms refer to the following:

Hazard – a chemical or physical condition that has the potential for causing damage to life, health, property or environment. Most hazards are dormant or potential, with only a theoretical risk of harm, i.e. the situation has the potential to be hazardous, so no concretisation of people, property or environmental elements which can be harmed at a specific site is provided when speaking about hazard. A hazard is usually used to describe a potentially harmful situation, although not usually the event itself – once the event has started it is classified as an emergency or an incident [14,29,30].
Risk – a combination of the likelihood of occurrence and the magnitude of the unwanted consequences [5,14,29].
Threat – specific evaluation of potential harm/loss being inflicted on the actual targets [29,31]. The key difference between hazard and threat is that threat relates to known subjects/elements of the environment which may experience consequences. While hazard is the potential for causing harm, as stated above, the threat is a concrete/specific situation of subjects/elements of the environment being exposed to the hazard (the exposure pathway being clearly identified). The term has been selected to reflect the expected environmental consequences related to certain incident. Basically, the meaning of the term "threat analysis" is similar to the term "consequence analysis" in the framework of risk assessment, however without the consideration of probabilities and/or frequencies. So, the key difference between threat and risk is that threat does not specify likelihood of the consequences in question. The benefit of introducing threat into LUP is two-fold:
- A land-use plan, as a product, does not involve a notion of likelihood of using land, so risk does not seem an efficient basis for determining actual and neighbouring land uses (e.g. no matter the probability of an industrial accident a society does not allow/confirm/incorporate casualties in a land-use plan but rather deterministically decides about land uses in the surroundings; nevertheless, probabilistic approach may effectively inform a decision about which type of land use seems to be most appropriate).
- Environmental consequence consideration in the land-use plan enables specification of conditions for neighbouring land uses, as well as organisational and architectural conditions and solutions

for urbanisation (e.g. potential of an accident which requires an evacuation of citizens in the neighbourhood may guide the design of transport infrastructure; as stated above, explicit consideration of probability of casualties is not praxis in land-use planning).
Land-use planning – refers to the process of generation of land-use plans (elaboration of plans) [28]. The phase of plan implementation (i.e. checking conformity in the approval process of the development proposals, licensing) is excluded from the understanding of this term; see also Fig. 4.
Environmental threat vulnerability is the state or characteristic of the environmental component which is the receptor of a negative change (effect) due to an accident involving hazardous materials [32,33]. It describes the level of susceptibility of the environmental component to being harmed due to an accident involving hazardous materials; or, inversely, the degree to which an environmental system, or a part of a system (a component), possesses resilience and resistance to the specific consequences of an accident [34]. For example, different buildings express different resistance levels (or vulnerability) to overpressure; or, not all rivers express the same level of self-purification after an incidental pollution event. Eventually, the environmental threat vulnerability is a measure (a yardstick) of sustainability of an environmental element/component when exposed to a specific accidental effect (e.g. this measure answers the question whether the salmon fish will survive the expected concentrations of a hazardous substance in a specific river section after an accidental spill). Environmental components include humans, natural ecosystems (fauna, flora), water, air, infrastructure (buildings), etc.
Spatial attractiveness – in the context of land-use planning the term attractiveness relates primarily to the economic efficiency (benefit) of a site where a development proposal is going to be realised, e.g. morphology of the terrain, availability of infrastructure (roads, electricity, etc.), water, workforce, etc.

2. Methodology

2.1. General

The method introduces the threat index as a tool for distinguishing between different consequences expected on actual environmental components. The consequences are presented in relation to a GIS unit. The numerical expression of a threat index represents different levels of threat. In its essence, the threat index builds on a consequence-based approach of risk assessment and combines it with the vulnerability of targets – receptors of consequences. As such, it requires the identification of accident scenarios with a consideration of the spatial distribution of physical effects. Accident scenarios are selected based on their relevance for land-use planning. This means that all scenarios having impact outside the plant limits, no matter the frequency, need to be considered. Such an approach does not exclude "low probability high consequence" situations (scenarios). It is adequate for two reasons: first, both possibility of an accident and the magnitude (scope) of its consequences are evaluated, and second, land-use planners and all parties in the process of plan approval get confidence that consideration of potential accidents was comprehensive and complete (contribution to trustworthiness and transparency of the overall LUP process).

2.2. Requirements of spatial planners for the methodology

In the process of conceptualisation and early design of the methodology, a number of workshops and discussions were organ-
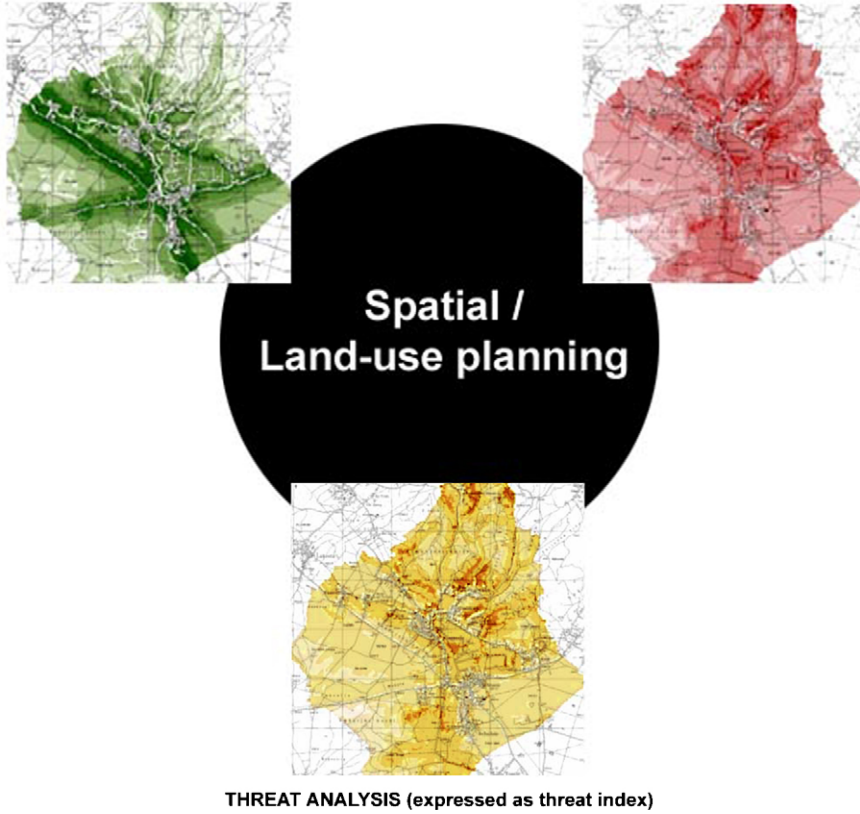
Fig. 2. Introduction of threat analysis into the existing spatial suitability approach.
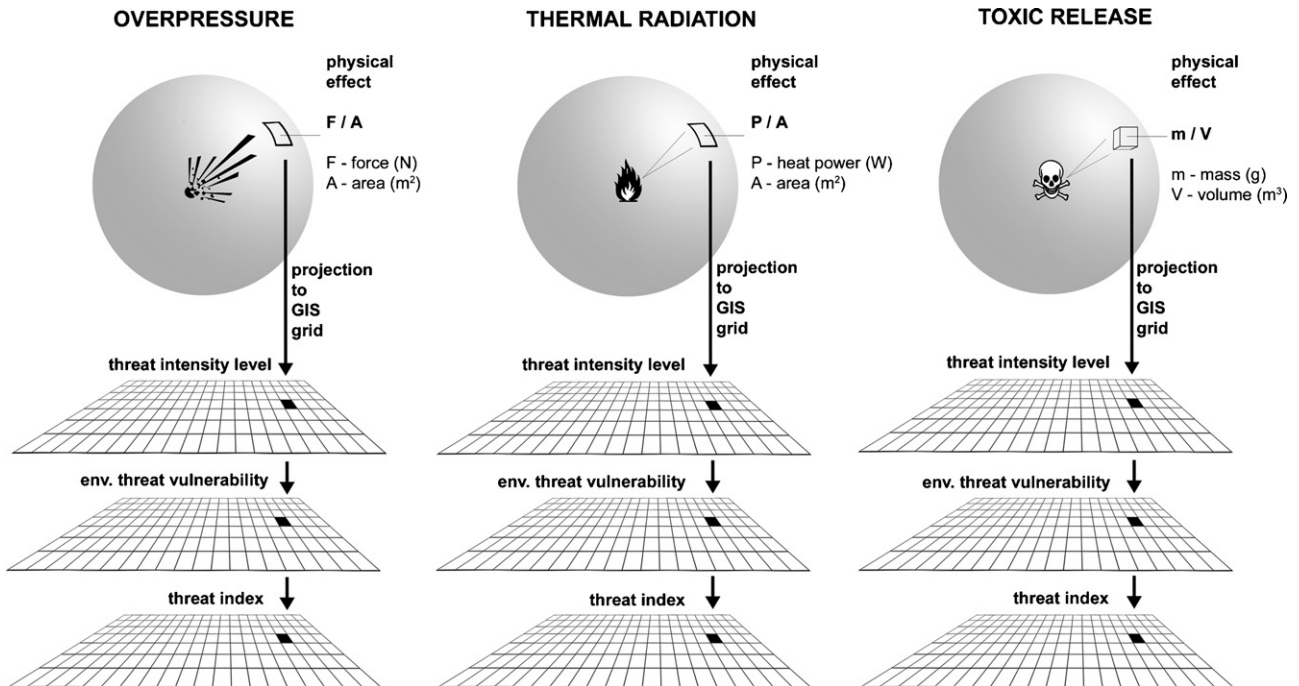

Fig. 3. Schematic presentation of threat index identification.

ised. Officials from the Municipality of Koper, representatives of Seveso II establishments located in the Municipality of Koper, land-use planners and risk assessors participated in these workshops. A summary of the discussions in terms of requirements for the methodology is included in Appendix A.

2.3. Description of the key features of the method

2.3.1. Threat index

Following the requirements for the methodology (see Appendix A), the introduction of the threat index is designed as an additional, i.e. the third, component to the already existing spatial attractiveness analysis and environmental vulnerability analysis of the spatial suitability approach in the framework of the Slovenian land-use process (Fig. 2). The main advantage of the approach is that it can provide preliminary guidelines for allocation of new hazardous establishments, and acts as a controlling instrument for development proposals around existing ones.

The approach of analysing and combining environmental vulnerability and spatial attractiveness into spatial suitability has been in practice in Slovenia since the early 1990s [35–40]. The concept is that it is possible to evaluate how attractive a certain piece of land is for a particular activity, and how vulnerable is a particular environmental component on the very same piece of land to the particular impact of the same activity. By superimposing these two values we can obtain an evaluation which piece of land is better or worse for allocation of a particular activity. When making this analysis by means of GIS it is easy to geographically identify these better and worse sites. The approach is now standardised in the framework of LUP in Slovenia.

Threat analysis resulting in a definition of a threat index consists of the following steps (the process is schematically presented in Fig. 3).

2.3.1.1. Step 1.
Quantitative assessment of the outcomes of an incident (e.g. fire, explosion, toxic cloud) and their physical effects (overpressure, thermal radiation, toxic concentrations in the air) is made by using standardised and widely accepted models [29,41], e.g. TNT, Baker–Strehlow for explosions, Pasquill–Gifford model (Gaussian dispersion) for dispersion in the air. In addition to these, threat analysis also involves, based on the accident scenario, quantification of toxic concentrations in water for the purpose of evaluation consequences for both water biota and humans (e.g. loss of drinking water source). Different dispersion models could be used for these quantifications, e.g. Stream model [42]. This step is the initiating step of consequence estimation and represents the incident outcomes obtained by scenario analysis, associated with the impact on the surroundings that could develop from a certain incident of interest. These outcomes serve as a basis for determining the threat intensity level of an incident in the following step.

2.3.1.2. Step 2.
Threat intensity level is a measure oriented to representing the magnitude and spatial distribution of the consequences associated with selected physical effects of incident outcomes (overpressure, thermal radiation, toxic concentrations in air and water). It takes into account a set of threshold levels concerning these consequences. In its core it is conceptually similar to risk severity [43–45]. The threat intensity is presented as a series of GIS based maps for selected physical effects, where each cell carries a value on a scale of 1–5 according to threshold level (1 – low, 5 – high), based on e.g. TEEL or ERPG values for the evaluation of threat intensity to humans, or concentration levels with dose assessment (e.g. LC_{50} or LD_{50} for fish for the evaluation of threat intensity to a river's or lake's biota). One should note that measures like Probit model results are not applicable in the LUP process, since they describe human death probability (expectation of human death from industrial accidents is not applied in land-use planning, due primarily to ethical and equity reasons). Probit model results other than zero, if attempted to be applied in land-use planning, would most probably lead to strong societal disagreements and conflicts, with the eventual result of not approving a plan, in spite of the accidental context of the issue. On the other hand TEEL and ERPG values constitute a common basis for emergency planning.

2.3.1.3. Step 3.
Environmental threat vulnerability analysis of potential receptors (humans, natural resources, built environment) located in the vicinity of hazardous industrial establishments. Environmental threat vulnerability, as used in this method, is defined in the introduction. Compared to environmental vulnerability defined in the ARAMIS project [43], the environmental threat vulnerability proposed in this paper answers not only the question which element is more precious to us, i.e. the question of weights assigned to the vulnerability of humans, material values and nature, but also whether the environmental element of interest will withstand the threat intensity level it is going to be exposed to in the case of an accident.

The environmental threat vulnerability is expressed as a ratio of the expected environmental damage/loss to the maximum possible damage/loss on a scale of 0–100%, translated into a scale of 1–5. The scale is based on pre-set criteria for exposure and received amount of energy/mass, i.e. dose, taking into account the probability whether the actual environmental element will withstand this dose (1 – no effects, 2 – negligible effects, 3 – reversible effects, 4 – irreversible effects, 5 – destruction/loss). This probability assessment is derived as expert opinion, taking into account, e.g. construction quality standards, building and architectural codes of practice, information on the sensitivity of specific population groups, etc. Presentation of the vulnerability is then provided for each grid cell.

The thresholds may also consider passive and active protective measures designed by municipal policies or experience of particular sectors, such as the sector for civil protection and rescue. In the case that no specific thresholds are provided, the ones presented in Table 1 could be used.

The result of environmental threat vulnerability analysis is a series of GIS based maps for selected environmental elements and certain physical effects of an incident. When combined with threat intensity level maps, threat index maps are produced, see Step 4.

Table 1
Thresholds to be applied in environmental threat vulnerability analysis [46–49]

Environmental threat vulnerability – reference values					
Damage/loss level	Effects	Overpressure (kPa) [46,47]	Thermal radiation (kW/m^2) [48]	Toxic release to air [49]	
1 – Low	No effects	<2.1	<4.5	<TEEL 1	<ERPG 1
2 – Low to medium	Negligible effects	2.1–6.9	4.5–12.5	TEEL 1	ERPG 1
3 – Medium	Reversible effects	6.9–13.8	12.5–25	TEEL 2	ERPG 2
4 – Medium to high	Irreversible effects	13.8–20.7	25–37.5	TEEL 3	ERPG 3
5 – High	Destruction/loss	>20.7	>37.5	>TEEL 3	>ERPG 3

Table 2
Combinations of threat intensity level and environmental threat vulnerability as a basis for the determination of threat index

Environmental threat vulnerability level	Threat intensity level				
	1	2	3	4	5
1	1	1	2	3	4
2	1	2	3	3	4
3	2	3	3	4	4
4	3	3	4	4	5
5	3	4	4	5	5

Note: Each value is assigned to a specific GIS grid cell in the area under consideration. The product of this assignment is a threat index map.

2.3.1.4. Step 4. Threat index expresses the degree of threat to a specific environmental element in the case of an accident.

The index has values ranging from 1 to 5 which are established by combining values on a 1–5 scale for both threat intensity level and environmental threat vulnerability. The combinations are presented in Table 2. The table is similar to an ordinary risk matrix which combines the frequency/probability of an accident and the severity of its consequences.

A threat index map may serve as a support in the process of revising the land-use plan around existing hazardous installations and as a guideline for developing a new plan or finding a suitable location for a proposed development project. If there are site alternatives for allocating hazardous industrial installation, threat index results could be used to evaluate which alternative would cause the least threat.

The threat index map also represents the basis for argumented discussion with those who live, work and/or place values in the affected area, and have, therefore, the right to be included in the final determination of the use of land, according to physical planning legislation in Slovenia [50].

2.3.2. Possible developments of the LUP process in Slovenia in terms of involving threat analysis

The existing land-use planning process in Slovenia is schematically presented in Fig. 4. It consists of four main steps. It is evident that neither hazard, threat nor risk analysis/assessment are involved in this process. However, risk assessment is required in the implementation stage – step 5 – as a part of the environmental impact assessment (EIA) process during the licensing procedure [50,51]. Such an approach is not in accordance with the Seveso II Directive which requires consideration of risk assessment results in the LUP process as a means of minimising the consequences of accidents. A suggested improvement of the planning process so as to meet this requirement is presented in Fig. 5. It divides step 2 into two sub-steps, extends the technical basis by general terms for siting of hazardous installations, provides preliminary determination of appropriate distances between a hazardous installation and vulnerable surrounding land uses, and introduces strategic environmental assessment (SEA) as a tool for identifying the best plan alternative also in terms of threat. In addition, it requires continuous monitoring of the plan implementation (loop from step 5 to sub-steps 2a, 2b, 3, and 4). Such a feedback enables prevention of conflicting spatial development around hazardous installations by means of maintaining proper distances as long as needed.
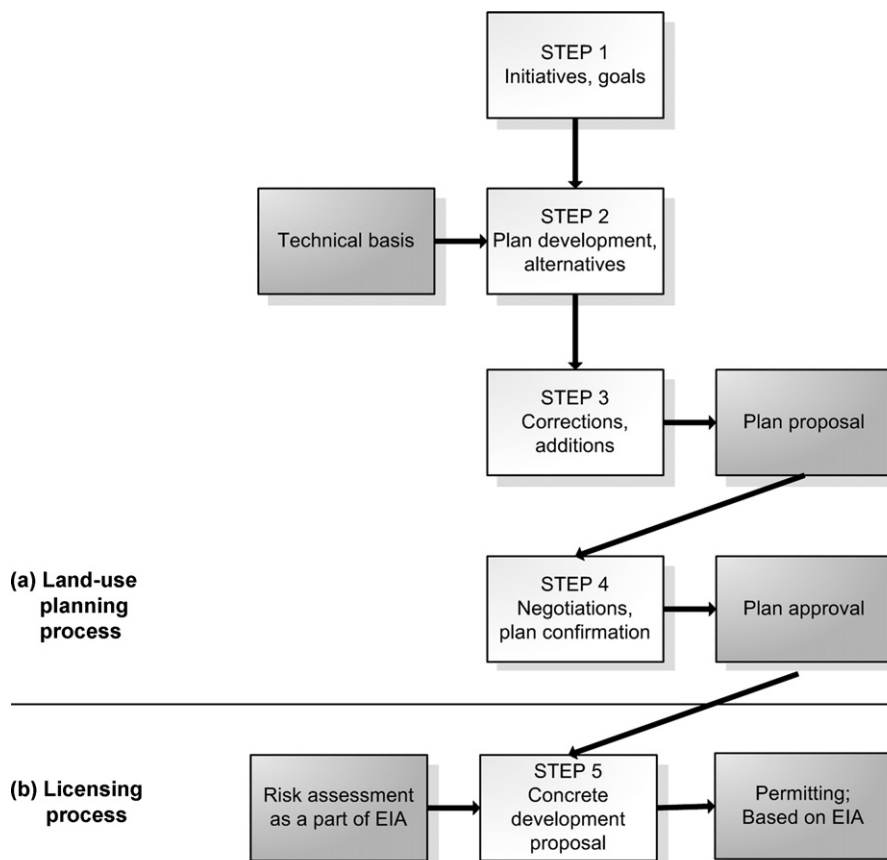

Fig. 4. Schematic representation of the current land-use planning process in Slovenia (a) and consideration of risk assessment in the licensing process (b).
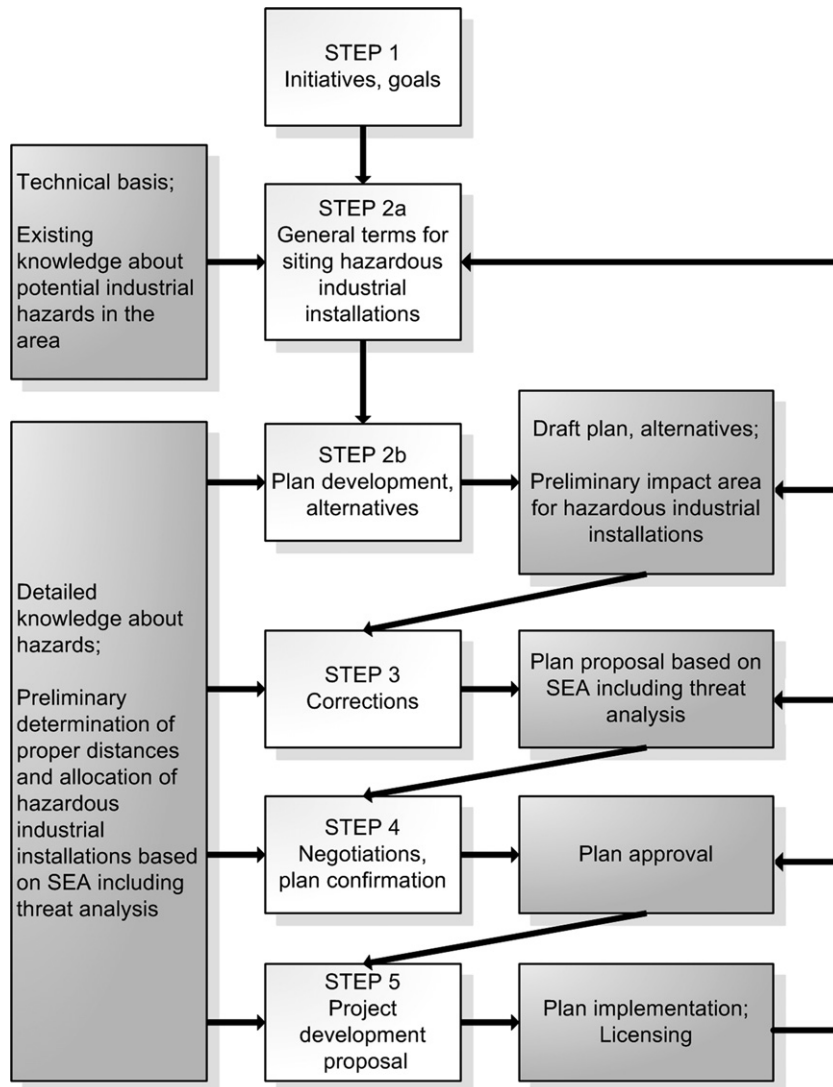
Fig. 5. Schematic representation of the proposed land-use planning process in Slovenia.
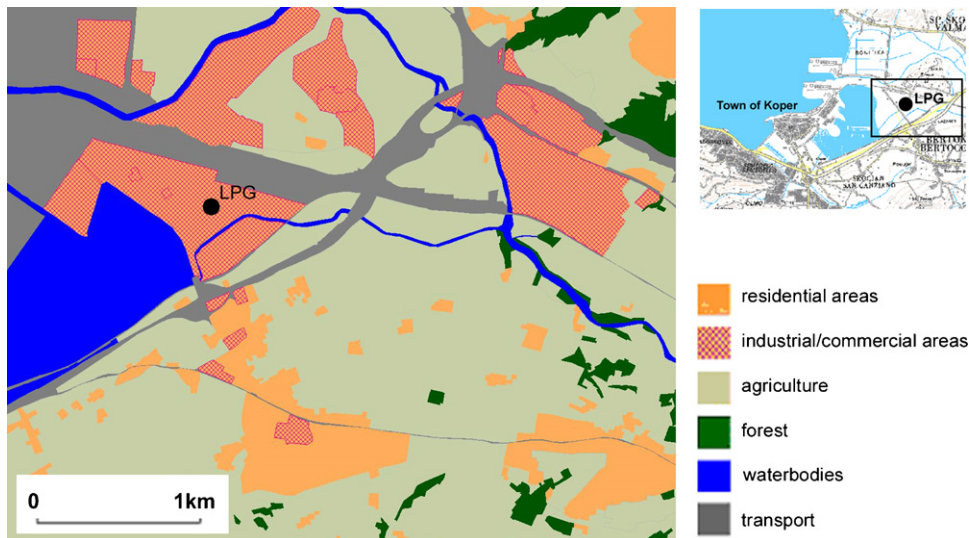

Fig. 6. Existing land-use plan for the area around the LPG storage facility.

3. Illustration of the methodology – LPG storage facility and the renewal of the land-use plan for the Municipal plan of Koper

3.1. General

Municipality of Koper is located in a south-western part of Slovenia, and is covering a majority of Slovenian coastal area. The main economic activities in the municipality are tourism, agriculture and industry.

The town of Koper has approximately 25 000 inhabitants. The average population density is 155 persons/km^2.

The characteristic landscape around the LPG storage facility is agricultural land, formerly salty marsh, dried out through history.

Fig. 6 shows a section of the existing land-use plan for the Municipality of Koper around the LPG storage facility – a Seveso II establishment, which was used as a case study for illustrating the methodology. The land-use plan is currently under the renewal process.

3.2. LPG storage and handling facility

The LPG storage and handling facility is an upper tier Seveso II establishment, located in the industrial/commercial zone to the north-east of the town of Koper.

The operations include:

- Loading, unloading and storage of LPG; total storage capacity is 450 m^3 in three 150 m^3 vessels.
- Filling of LPG into 10 kg steel containers for households.
- Distribution of LPG for industry by road tankers and 10 kg steel containers to households.

Adjacent to the facility three manufacturing organisations employing approximately 120 persons are located. The nearest residential area is 150 m north of the site.

South-west at a distance of approximately 400 m from the establishment, a salty shallow lake is situated (formerly sea) and is categorised as a special environmentally protected area – Natura 2000 site [52]. South-east, at a distance of 500 m, the protected tree line is located.

Based on the findings of formal safety report [53] and subsequent discussion with the author of the report and managers of the establishment, the following scenarios are considered as relevant for LUP (a consequence-based approach used for the selection of scenarios, see also Section 2.1):

(a) Boiling liquid expanding vapour explosion (BLEVE) of the 150 m^3 storage vessel.
(b) Vapour cloud explosion (VCE) after a spill of LPG during loading/unloading of road tankers due to a break (failure) of a flexible hose.

Small leakages from standard 10 kg steel containers of LPG are not classified as relevant for LUP consideration.

Scenario (b) is treated both as an independent scenario, as well as an initiating situation for the development of scenario (a). In the latter, VCE causes damage to valves and connecting piping of the adjacent 150 m^3 storage vessel, as well as to a fixed fire extinguishing/cooling system at the loading/unloading and storage area, with additional major release of LPG leading to a major fire and the final event of a BLEVE of one of the 150 m^3 vessels [14,53]. The safety report and analysis conclude that a jet-fire at the end of the broken flexible hose or damaged fixed piping could not cause BLEVE, since direct impingement is excluded due to the parallel position of the vessels and the road tanker (with a maximum 5 m long hose) at the loading/unloading facility, the position of piping below the vessel, and the low hydrostatic pressure of LPG in the damaged piping. The primary consideration of the scenario in the safety report is therefore the initial spill of LPG. After explosion of a vapour cloud a fire occurs at the loading/unloading and storage area due to major release as a consequence of the damage to the installation caused by VCE. This major fire causes BLEVE of one of the two undamaged vessels. The possibility of two simultaneous BLEVE was excluded due to the intensive evaporation of the spilled LPG, and the solid separation walls between the vessels which prevented spilled LPG from flowing and formed a fire under both the vessels, while a domino effect (one BLEVE at a time) would have an almost identical impact area as a single one. Also, additional damage in the surroundings due to a second BLEVE would be of less importance than the first one.

The source of ignition of the vapour cloud is assumed to be at a distance of 50 m (the distance to the facility boundary where ignition sources are not controlled).

The BLEVE scenario assumes that the LPG is partly exploded, partly burned and partly evaporated and dispersed. The analysis was made for 72 tonnes of LPG [53] (maximum vessel capacity – conservative approach) and 36 tonnes (half vessel capacity – reasonable approach). The modelling calculations were made using PHAST v6.1 software [53].

3.2.1. Threat analysis for overpressure
3.2.1.1. Threat intensity level. The results of the threat intensity level for overpressure for the BLEVE scenario are summarised in Table 3 and presented in Fig. 7.

3.2.1.2. Environmental threat vulnerability. The results of the environmental threat vulnerability analysis for overpressure in the vicinity of the LPG storage facility are presented in Fig. 8.

The highest levels of vulnerability are observed in industrial/commercial, residential (possibility of injuries, material damage) and protected natural areas.

3.2.1.3. Threat index. Threat index maps are presented in Fig. 9; the key for the determination is presented in Table 2.

Both figures show the highest levels of threat (categories 4 and 5) within the industrial/commercial area, posing a threat to several neighbouring facilities/buildings. Note that threat indices are presented up to the distances determined by the threat intensity levels; beyond these distances no threat indices are indi-

Table 3
Threat intensity level for overpressure for BLEVE scenario of 150 m^3 LPG vessel

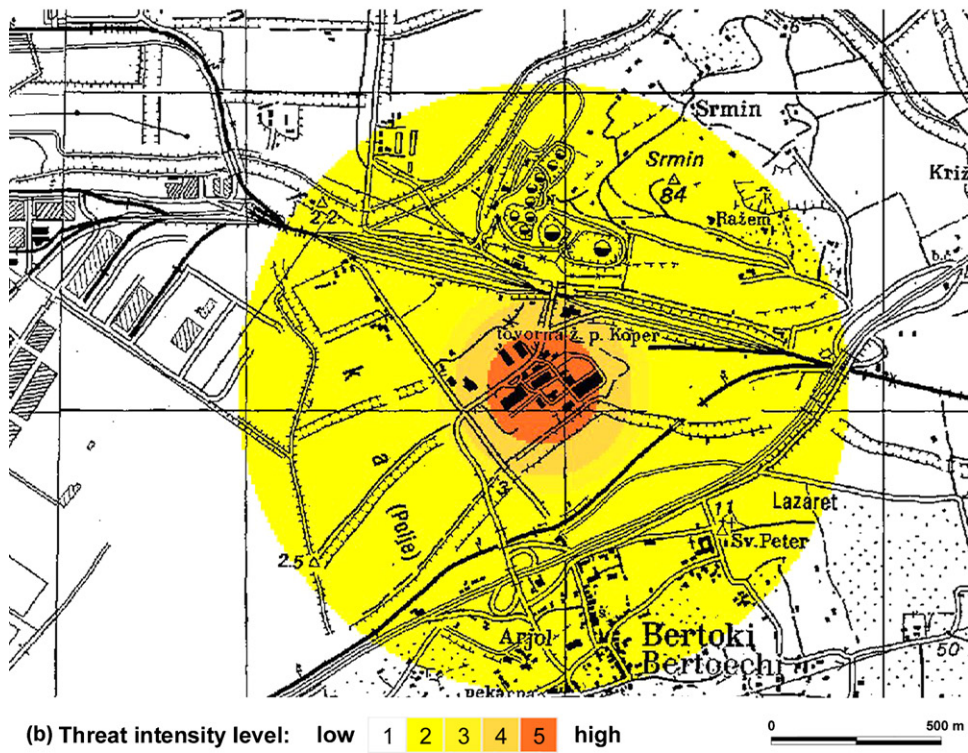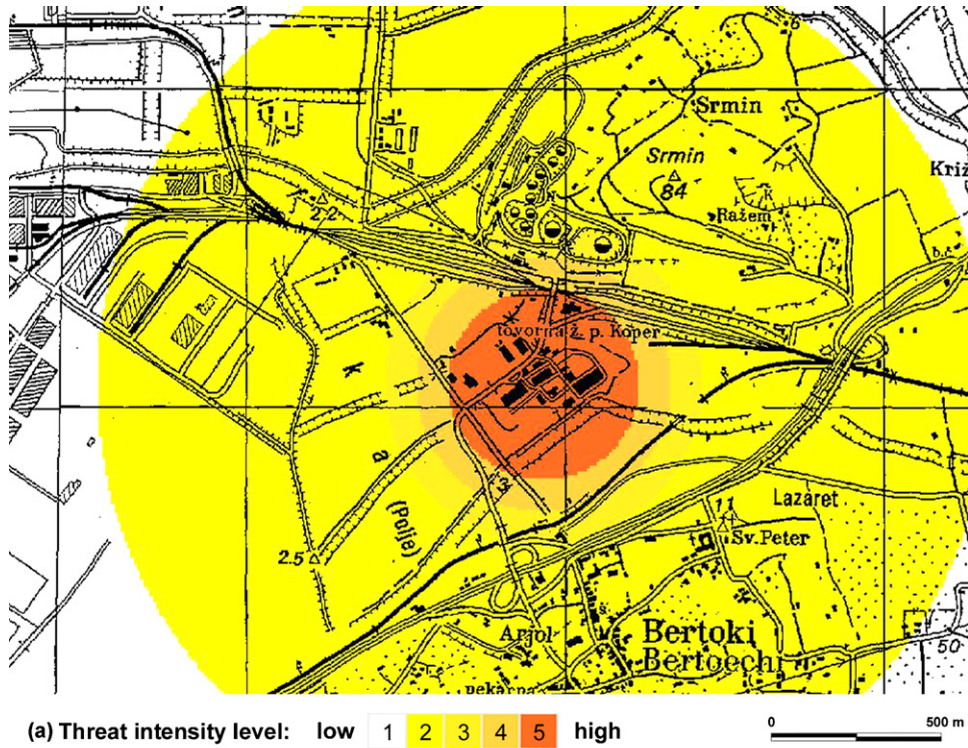| Threat intensity level	Reference values for overpressure (kPa)	Distance – impact radius (m) (72 tonnes)	Distance – impact radius (m) (36 tonnes)
5 – High	>20.7	<275	<180
4 – Medium to high	13.8–20.7	275–355	180–280
3 – Medium	6.9–13.8	355–500	280–340
2 – Low to medium	2.1–6.9	500–1370	340–960
1 – Low	<2.1	>1370	>960

Fig. 7. Threat intensity level for overpressure – conservative approach 72 tonnes (a) and reasonable approach 36 tonnes (b).

cated, no matter how vulnerable environmental components may be.

3.2.2. Threat analysis for thermal radiation

3.2.2.1. Threat intensity level. The results of the threat intensity analysis for the thermal radiation scenario are analogous to the ones for overpressure and are summarised in Table 4.

3.2.2.2. Environmental threat vulnerability. An environmental threat vulnerability analysis for thermal radiation was made similar to the analysis for overpressure. The results are presented in Fig. 10.

Again, the highest levels of vulnerability were observed in industrial/commercial, residential, agricultural and natural areas.
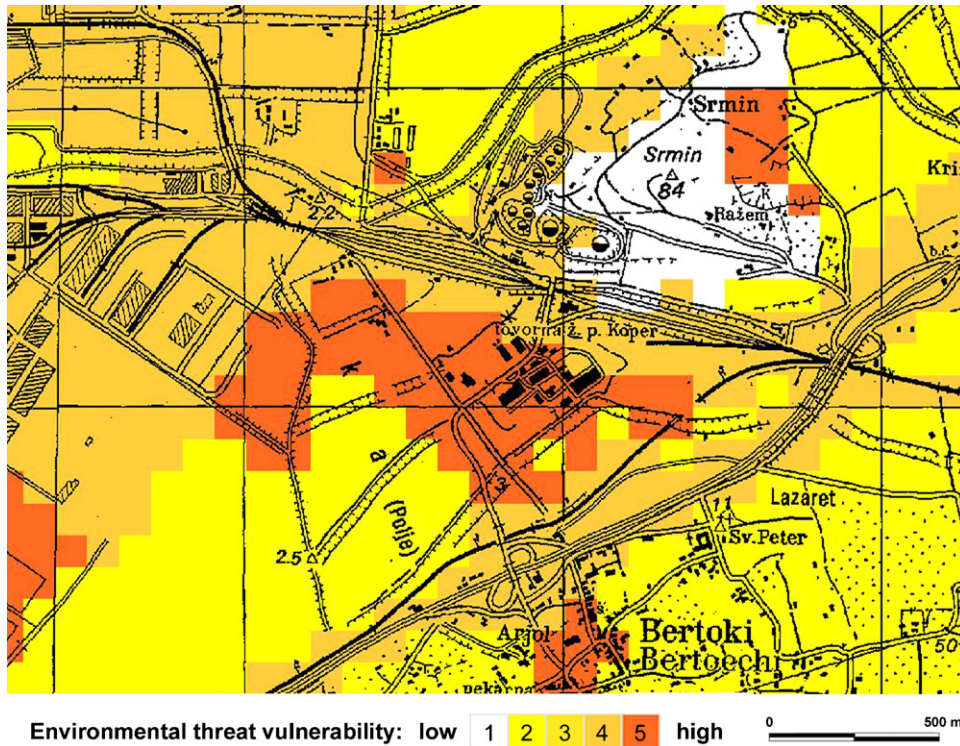
Fig. 8. Environmental threat vulnerability for overpressure in the vicinity of the LPG storage facility.

3.2.2.3. Threat index. Threat index maps are presented in Fig. 11. The results are similar to those for overpressure, only distances in the conservative approach are smaller.

3.2.3. Threat reduction measures

Based on the results of threat analysis, the proposed threat reduction measures are:

(a) Replacement of the flexible hose with a mechanical arm. By replacing the flexible hose with a mechanical arm, the possibility of an initiating event, i.e. a spill as a result of a hose failure during loading/unloading of road tankers is eliminated. The decoupling mechanism of the mechanical arm allows the release of only 0.1 l of LPG [53,54]. This measure eliminates both the VCE and the BLEVE scenario.
(b) Burial of the 150 m³ LPG vessels, i.e. underground storage. Such a technological change would eliminate the BLEVE scenario, but it is more expensive than the installation of a mechanical arm. In addition, the VCE scenario still remains as possible.
(c) Guiding future land-development away from the risk source. This approach is less favoured by establishment managers, since certain areas potentially suitable for development are left unused, functioning as safety buffer zones. Management of such buffer zones is usually the responsibility of the authorities; however, costs for maintaining the zone are covered by the risk source.

In the context of both economic and risk considerations, the most reasonable option is option (a). Option (b) is significantly more expensive in terms of investment expenditures than option (a), while option (c) is basically a prolongation of the existing situation that is not desirable (tolerable) any longer, either by the Municipality of Koper or by other users/owners of land in the buffer zones. Further, the risk reduction of the three measures is not the same. Option (a) provides most efficient risk reduction, since it eliminates both VCE and the BLEVE scenario. Option (b) is less effective than option (a), since it eliminates BLEVE scenario but not the VCE. Option (c) does not prevent either the VCE or the BLEVE scenario, but is effective in terms of risk reduction and elimination of the consequences in the surroundings by guided land use and establishment of the buffer zone. Taking into account these characteristics, managers of the LPG establishment selected option (a).

3.3. Results in terms of possible changes to the land-use plan of the Municipality of Koper

The existing situation without implementation of the threat reduction measures (a and b) requires in the context of LUP a formal safety buffer zone around the LPG facility (threat reduction measure c), see Fig. 12. So far, such a zone has not been formally established, however no urbanisation was allowed around the plant, only agricultural activities. If the buffer zone were to be established, it would be under constant development monitoring, where no develop-

Table 4
Threat intensity level for thermal radiation for BLEVE scenario of 150 m³ LPG vessel

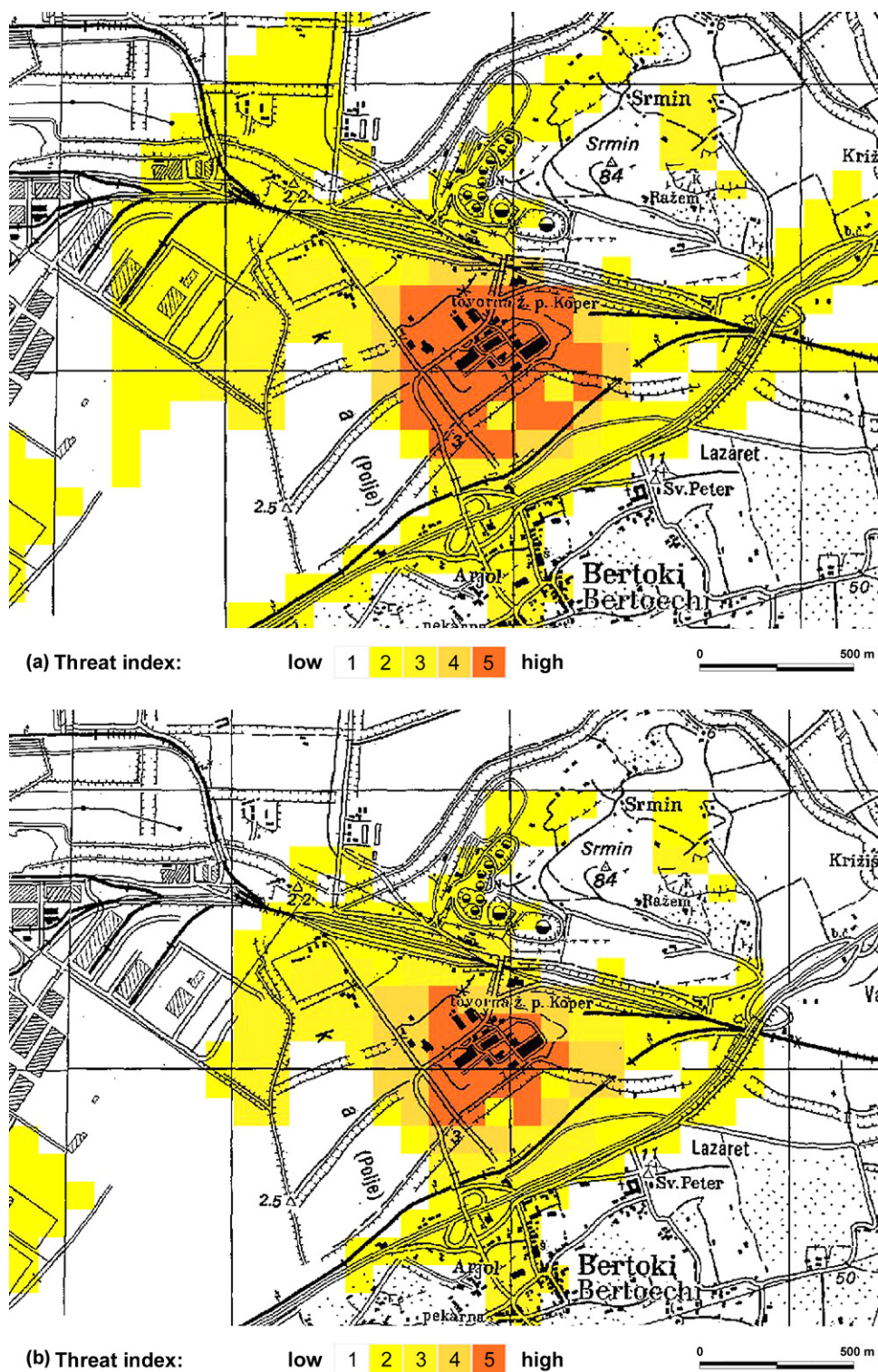| Threat intensity level	Reference values for thermal radiation (kW/m²)	Distance – impact radius (m) (72 tonnes)	Distance – impact radius (m) (36 tonnes)
5 – High	>37.5	<210	<160
4 – Medium to high	25–37.5	210–250	160–190
3 – Medium	12.5–25	250–370	190–290
2 – Low to medium	4.5–12.5	370–650	290–500
1 – Low	<4.5	>650	>500

Fig. 9. Threat index for overpressure – conservative approach 72 tonnes (a) and reasonable approach 36 tonnes (b).

ment would be encouraged. Location, construction and operational permits at larger distances than the buffer zone radius would be a question of case-by-case considerations by the authorities.

On the other hand, if either of the other two threat reduction measures were applied – measures (a) and (b) – the consequent reduction of the impact area could make future uses of the sur-

roundings more liberal and oriented towards stronger economic development. Possible changes in that context are presented in Fig. 13 and in Tables 5–7. This simulation was a basis for developing a number of LUP alternatives for this area in the ongoing process of renewal of the municipal plan. Outcome based on specific economic studies, discussions and negotiations among potential
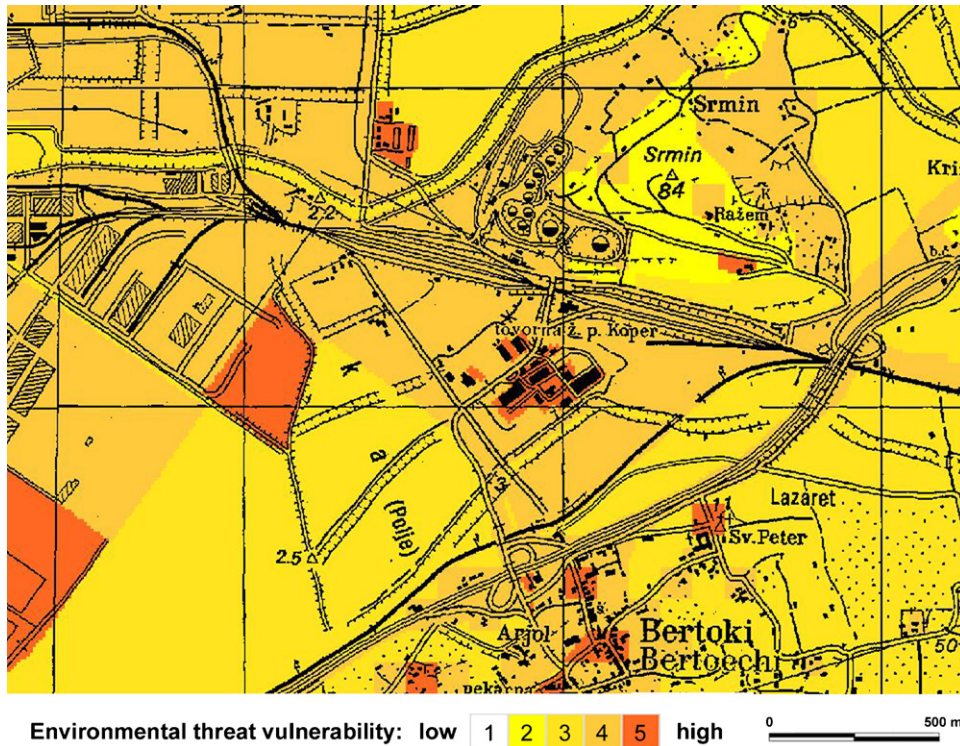
Fig. 10. Environmental threat vulnerability for thermal radiation in the vicinity of the LPG storage facility.

Table 5
Current property values in Koper region

Land use	Price (€/m²)
Agriculture, pastures	8
Vineyards/olive groves	30
Development plots	150
Individual housing (U1)	700
Blocks of flats P/4 (U2)	3500
Commercial (U3)	1000

Table 7
Land value gain after BLEVE scenario elimination

Land use	Area (ha)	Price (€/m²)	Value (M €)
Agriculture, pastures	10	8	0.8
Individual housing (U1)[a]	6	700	16.8
Commercial (U3)[a]	3	1000	12.0
Sum			29.6

[a] U1 and U3 categories take into consideration urbanisation density factor of 0.4.

investors (future land users) is pending; SEA is to be performed to help identifying the best alternative; agreement and approval of the renewed plan is expected by the end of the year.

4. Discussion

Testing of the methodology revealed several important topics which require attention and discussion. These are summarised as follows:

(a) The role of accident scenarios for the determination of impact area.

One should be aware of the implications of the accident scenarios at two levels. The first is selection of a scenario which has an impact on land-use planning. It is obvious that for this purpose some kind of preliminary threat or risk analysis should be made first, providing a geographical indication of the scope of the consequences before detailed threat analysis is performed. In land-use planning impacts of the scenario are relevant in terms of both human interests for land use and environmental protection. How much land a certain accident scenario "covers" (i.e. how big is the impact zone) and what environmental qualities may be degraded or lost in the case of an accident is ultimately a question of acceptability. Whether or not accident scenarios clearly and adequately consider and asso-

Table 6
Implication of the BLEVE scenario – realistic approach (36 tonnes) on land value loss due to no land development; selected categories of thermal radiation and overpressure

Values of land according to different uses based on Table 5 (M €)							
Physical effect – selected reference values	Distance to selected reference values (m)	Area associated to reference values and distances (ha)	Agriculture/fields, pastures	Vineyards/olive groves	U1[a]	U2[a]	U3[a]
BLEVE 36 tonnes							
12.5 kW/m²	290	22.4	1.8	6.7	62.8	314.0	89.7
37.5 kW/m²	160	5.0	0.4	1.5	14.0	70.1	20.0
13.8 kPa	280	20.7	1.7	6.2	57.9	290.0	82.8

[a] U1, U2 and U3 categories take into consideration urbanisation density factor of 0.4.
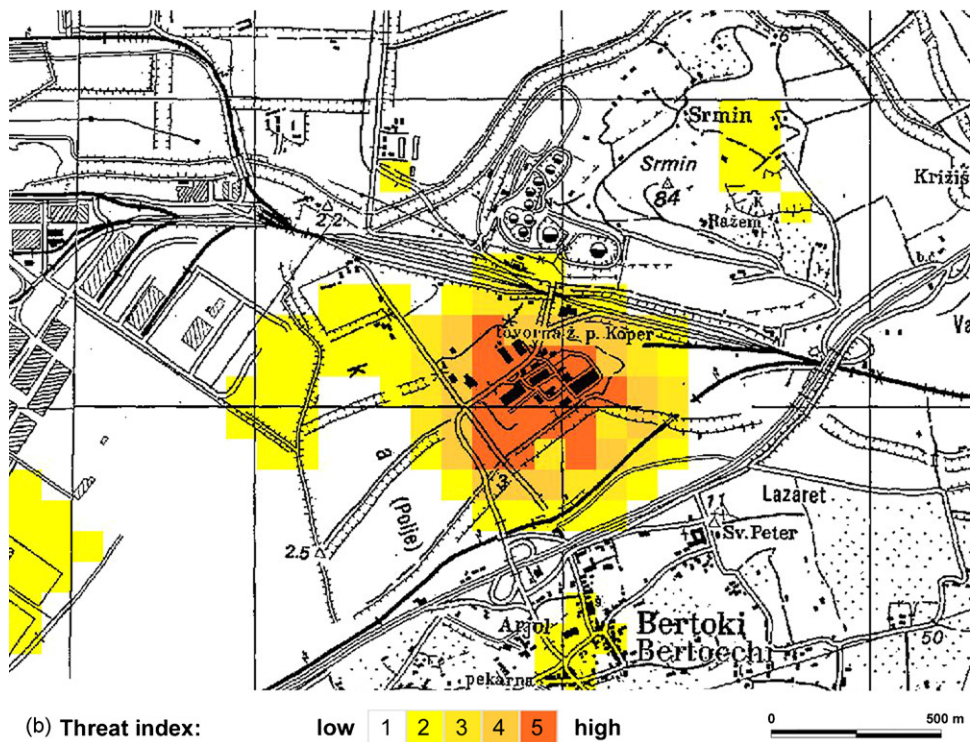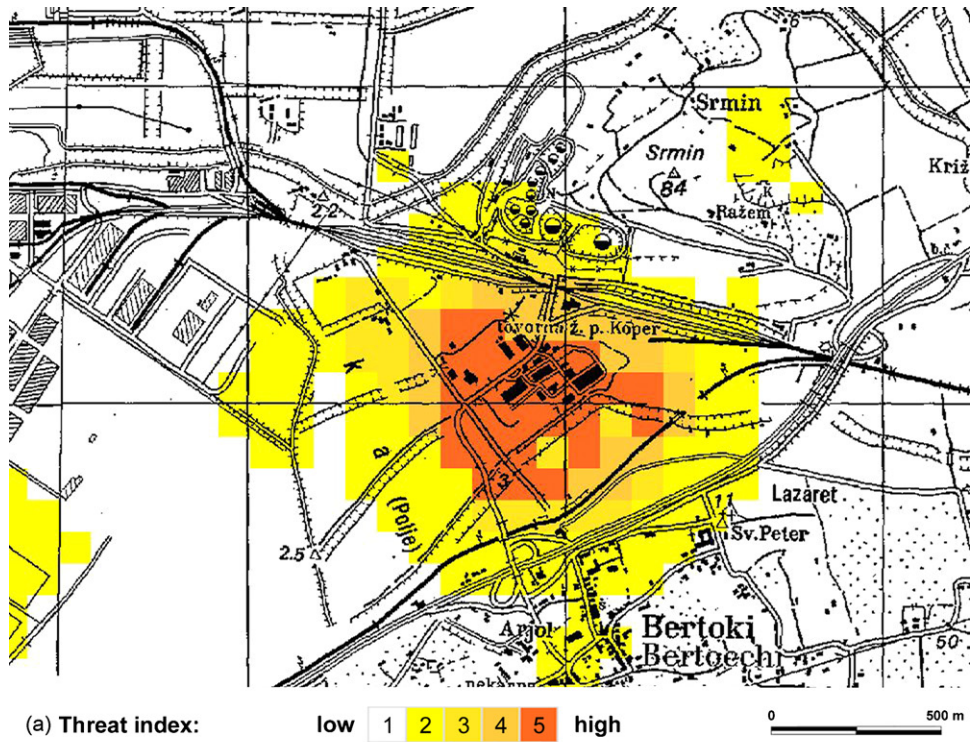
Fig. 11. Threat index for thermal radiation – conservative approach 72 tonnes (a) and reasonable approach 36 tonnes (b).

ciate these issues is a question to be identified during the LUP process.

The second level is accuracy or rather the trustworthiness of the scenario. If the uncertainty of the selected scenario is too big and subsequent alteration of the impact area too significant, the land-use planning process may reject the approach as too vague, or too sensitive, or non-robust. Namely, specific

land uses in an actual land-use plan have sharp and static borders; there are no "grey" zones between neighbouring land uses, which would, for example, imply uncertainties of the accident scenario (e.g. alteration of the impact zone due to different modelling assumptions causing variations of the amount of released toxic gas). If scenario uncertainties are so big that they affect LUP process additional efforts should be made either to identify
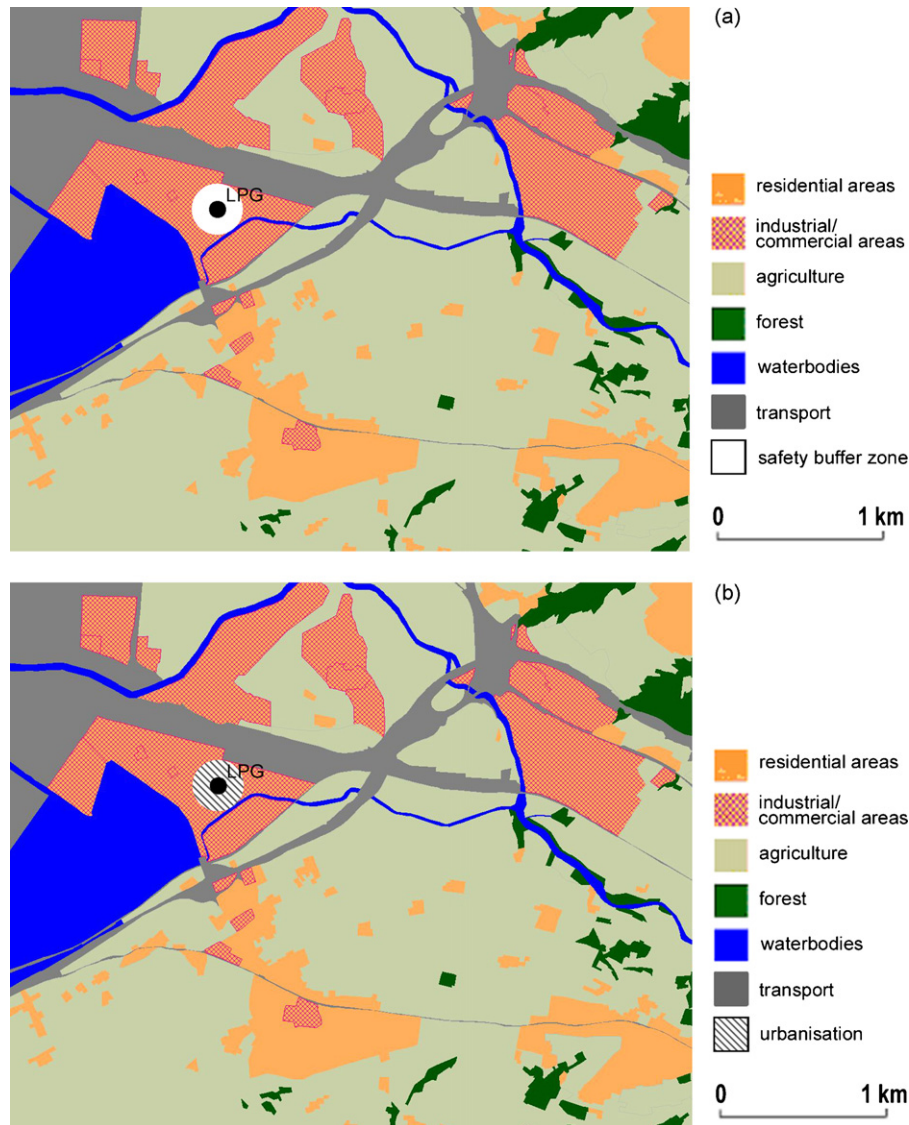
Fig. 12. Possible changes of the land-use plan around the LPG facility: (a) establishment of the formal safety buffer zone if no threat reduction measures are implemented at the facility, (b) possibility of different urbanisation after replacing flexible hose with a mechanical arm – see details in Fig. 13.

their sources, classify them into categories (e.g. epistemic or statistical) and find the means for their reduction, or to investigate what additional safety measures could be applied (improvement of the SMS at the plant) for the elimination of the scenario or diverting it into one with lower uncertainty, or to the one non-relevant for LUP.

To illustrate possible influence of modelling uncertainty, Tables 3 and 6 are merged into Table 8; the difference in impact areas for selected reference values is approximately within factors 1.6–2.1, when applying a conservative or realistic approach (different assumptions) to scenario analysis.

(b) Economic implications of threat analysis in the framework of LUP.

The expected financial loss or gain due to establishing buffer zones in the impact area (no development) or allowing land development (housing, commercial zone) may be considerable (Tables 5–7). Presentation of such results in a transparent way may support the land-use planning process as a vehicle for enforcing threat/risk reduction measures at certain installa-

tions. Actually, this has been the case in the Municipality of Koper; in the stage of reviewing the land-use plan, the Municipality, i.e. the local authority, required the managers of the LPG establishment to reduce impact area by applying either measure (a) or (b), see Section 3.2.3. As stated above, the managers of the LPG facility decided to install a mechanical arm at the loading/unloading facility, which is the most reasonable option (most benefits for least cost).

(c) Application of the method for new hazardous installations.

The method is designed to contribute to land-use management around existing hazardous installations, as well as to inform the search for suitable locations for new ones and to be used when preparing a new land-use plan. However, there are a number of issues related to the latter. The main problem here is a lack of information about new installations (technology, capacity, safety measures) in the early land-use planning phases. The solution for the LUP process in Slovenia is being sought in an additional methodological step in land-use plan development, as well as revision (amendment) of existing steps (see

Fig. 13. Illustration of possible land development scenario after elimination of the BLEVE scenario. Explanation of U1 and U3 is in Table 5.

Figs. 4 and 5). The main idea is that through strategic environmental assessment (e.g. assessment of alternatives of a land-use plan) the general terms and conditions for allocation of hazardous installations are provided, while in the following steps a precise siting process is applied along with the determination of appropriate distances, orientation, eventual buffer zones and use of land in the vicinity of the establishment – based on more specific information provided by the investors. In this phase guidelines for urban (traffic routes, allocation of vulnerable buildings – hospitals, schools, etc.) and architectural design would also be provided, with the goal of assuring the efficiency of emergency response, if needed. Application of the suggested guidelines, terms, and conditions would be realised in combined and harmonised processes of land-use planning, strategic environmental assessment and finally project level environmental impact assessment.

(d) Relation between risk assessment and threat analysis.

It is obvious that common risk assessment results could be efficiently used in threat analysis and vice-versa. The outcome in both cases is upgrading of the methods and improved land-use plans. No matter where the analysis starts, e.g. from consequence analysis in the framework of risk assessment through environmental vulnerability to threat index, or from environmental threat vulnerability through accident scenario

consequence analysis to threat index, the LUP process will gain a solid scientific basis for achieving long-term stable agreement among the stakeholders involved regarding uses of land around a hazardous installation. Nowadays, at least in Slovenia, no risk assessment or threat analysis for hazardous industry is formally applied at the level of land-use planning.

(e) Changes of safety management system.

Also relevant in terms of determining the scope of impact areas of the scenario are the factors of the safety management system (SMS) of the facility. These have also been addressed by the proposed method, however SMS can be changed within a short time period, while general land-use plans are made for longer time periods (10 or 20 years or even longer). In the case where violation of conformity with the land-use plan regarding safety is recognised, the responsible inspector (SMS is the subject of regular safety auditing and inspection) is obliged to require improvements for the purpose of harmonising the SMS and overall safety of the installation with the LUP. The need for continuous development monitoring around hazardous industrial installations is thereby evident.

(f) Who should make the threat analysis: risk assessors or land-use planners?

Our example showed that common scope and form of risk assessment results as provided in the formal safety report [53]

Table 8
Implication of the scenario uncertainty to the scope of impact area

Physical effect – selected reference values	Distance to selected reference values (m)		Impact area (ha)		Difference in impact area; ratio between conservative/realistic approach
	BLEVE 36 tonnes	BLEVE 72 tonnes	BLEVE 36 tonnes	BLEVE 72 tonnes	
12.5 kW/m^2	290	370	22.4	37.6	1.7
37.5 kW/m^2	160	210	5.0	10.4	2.1
13.8 kPa	280	355	20.7	33.8	1.6

were not sufficient in the process of renewal of the land-use plan. Consequently, one of the key questions was who is going to upgrade the results, i.e. who will perform the work represented by arrows in Fig. 3 and produce related GIS based maps with their proper interpretation for the purpose of the approval of the renewed land-use plan: risk assessors or land-use planners? The answer is, based on our experience, that this work could be properly done only within strong and continuous collaboration between the two groups of experts. This means that risk assessors should not just "throw their own results over the fence" to the land-use planners (i.e. just submit a safety report), thus trying to get back to their next risk assessment work as soon as possible. The collaboration should be maintained until the land-use plan in question is approved! Such a collaborative culture among risk assessors and land-use planners has still to be developed in Slovenia; we assume that a similar need can be found elsewhere.

The praxis of the implementation of the threat index will show how effectively Slovenia succeeded in avoiding such situations and conflicting developments as are presented in Fig. 1a and b. In this context it is important to note that the threat index approach is applicable not only for avoiding conflicts between industrial zones and outer land users but also land users in the industrial zones themselves. One of the examples of such applications is the allocation of process and other plants (e.g. storage facilities) in a way that prevents domino effects. The other could be a design and organi-

sation of the whole industrial zone that stresses vulnerability and importance of the common infrastructure in the zone, e.g. fire fighting installations or cooling water network needed for two or more plants/processes in the zone. Application of the threat analysis early enough in the design process is certainly in line with the preventive strategy of risk assessment and a good safety management system.

5. Conclusions

Threat analysis for hazardous industrial installations, as an approach to threat-informed land-use planning, enables transparent and understandable interpretation of threat for land-use planning purposes. It successfully combines consequence analysis results of quantitative risk assessment with environmental vulnerability analysis. As such the method presents a way of implementation of Article 12 of the Seveso II Directive. It can be used as an additional scientific basis for siting new hazardous industrial installations.

The results of our study also show the specific economic benefits of the approach in the Municipality of Koper. After testing the method on several other cases, its potential for general use will be assessed.

Appendix A. The requirements of spatial planners for the methodology and responses to these requirements

Phase	Description	Basic requirements	Responses to requirements and novelties
Phase 1: Conceptualisation	This step introduces threat index. The threat index converts classical hazard and risk assessment results into a form which is applicable in the process of land-use planning.	Maintaining current philosophy and practice of land-use planning; threat index should be directly applicable.	Legal and philosophical framework (current practice) for land-use planning remains as it is. In that context zoning policy/approach provides background for approval of spatial suitability for certain land use. The same profiles of expertise are involved in the planning process (e.g. sectoral planning, infrastructural planning, landscape architecture, urban planning, architecture, civil engineering); an additional expertise is industrial accidental risk assessment.
		Applying/maintaining approach of spatial suitability for development projects.	The combination of environmental vulnerability with spatial attractiveness analysis is the basis for determining spatial suitability. This approach is well known, well understood and widely accepted among stakeholders in Slovenia. The introduction of threat analysis into the land-use planning process does not change this approach, but follows it as much as possible. See Fig. 2.
		Holistic approach to environmental impacts.	Standard risk assessment usually focuses on consequences to humans. Threat analysis takes into consideration the environment holistically and addresses, besides humans, also nature, natural resources and the built environment, since they are all categories encompassed by the land-use planning process.
		Applying GIS tools.	Application of GIS tools is common, widely used and standardised.

Appendix A (*Continued*)

Phase	Description	Basic requirements	Responses to requirements and novelties
		Consideration of the need for small impact zones.	Each accident has its specific impact zone. Reduction and optimisation of the extent of impact zones is provided by means of accidental scenario analysis and enforced by the relevant technical and organisational measures at the installation for the purpose of limiting releases or reducing the likelihood of occurrence, or both. Associated with siting new installations small impact zones are imperative in the first place. In that sense the land-use planning process is recognised as a mechanism for enforcing technological optimisation for the purpose of reducing impact zones as much as possible.
Phase 2: Implementation design	Implementation should encompass environmental modeling and should allow qualitative and quantitative determination of threat in designated area.	Differentiation between existing and new installations; existing installations should be able to adapt to identified threat while the new ones should maintain conformity by continuous monitoring of land developments of neighbouring land use.	The method should differentiate between existing and new installations. For existing installations the technology, safety management systems (SMS), operational records, compliance status, standardisation etc. is known. Therefore, determination of impact zones for particular accident is relatively accurate. On the other hand, at the stage of preparation of a land-use plan for a new industrial zone, this information is not available. In such cases determination of impact zones is uncertain, so the method should reflect this issue. At the moment the method is tested for existing installations only. Regular auditing of SMS contributes to overall (safety) compliance assessment, which is a basis for prolongation of the operational permit of the establishment every five years. If violations of safety standards/expectations are recognised during the auditing, the inspector is obliged to decide whether to stop of the operation of the establishment or particular facility.
		Interpretation and presentation of threat analysis results for land-use planning purposes.	Commonly risk assessment results are presented in the form of probability for a certain accident consequence. Sometimes the extent and spatial distribution of these consequences are given. For LUP purposes spatial interpretation and presentation of risk consequences is the only form which is beneficial. In that context threat analysis end-points (expressed as threat index) are formulated accordingly.
		Transparency of the presentation of threat indices by means of GIS tools.	In the process of combining environmental vulnerability with spatial attractiveness into spatial suitability, each cell of a GIS grid has a particular value. These values are transparent, retrievable and justifiable. The same applies for threat, where threat index is assigned to each cell of the grid in the impact zone. The threat index combines environmental threat vulnerability and the threat intensity level.
Phase 3: Testing and approval	Testing should be done by means of a case study within revision of the land-use plan.	The method should be tested at the municipal level.	The method should be tested by means of a case study. The testing procedure should be clear and understandable for public participation purposes. The municipality of Koper and an LPG storage facility were selected as a case study.

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