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Quantitative hazard assessment for Zonguldak Coal Basin underground mines

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ABSTRACT

Underground coal mining is one of the most dangerous occupations throughout the world. The reasons behind an underground occupational accident are too complex to analyze mainly due to many uncertainties which may arise from geological, operational conditions of the mine or individual characteristics of employees. This study proposes implementing a quantitative methodology for the analysis and assessment of hazards associated with occupational accidents. The application of the proposed approach is performed on the mines of Turkish Hard Coal Enterprises (TTK). The accidents in TTK between the years 2000 and 2014 are firstly statistically analyzed with respect to the number, type and location of accidents, age, experience, education level and main duty of the casualties and also injuries resulting from such accidents. The hazards are classified as individual, operational and locational hazards and quantified using contingency tables, conditional and total probability theorems. Lower and upper boundaries of hazards are determined and event trees for each hazard class are prepared. Total hazard evaluation results show that Armutcuk, Karadon and Uzulmez mines have relatively high hazard levels while Amasra and Kozlu mines have relatively lower hazard values.

1. Introduction

Coal is produced by surface or underground mining. Mining is particularly hazardous because of the nature of the work carried out. Moreover, occupational accident risk in underground coal mines is much higher than in surface mining. Accidents are very complex and many factors can contribute to their occurrence. For these reasons, great efforts have been made to analyze the causes of accidents and many investigations have been carried out on the subject in literature [1–17]. The studies analyzing the certain type of accidents involve machine or equipment related accidents, accidents resulting from blasting, mine fires and explosion accidents, roof and side falls, mine floods, accidents due to behavioral factors [18–36]. Additionally, mine accident hazard analyses are carried out by Khanzode et al. [37–41]. The factors of coal mine accidents are differentiated and analyzed by Liang et al. at which the accident causation is divided into three as inherent hazards, technology equipment defects and safety management misconducts [38]. It is concluded that the level of technology and equipment determines the basic safety standards of the coal mine, and safety management is a powerful tool for improving the technology and equipment level. The study carried out by Khanzode et al. reveals that accidents related to machinery, ground-fall, housekeeping, roadways, and materials are the most frequent ones [37].

Different hazard assessment methods like regression models, distribution functions, hazard theories, fuzzy logics are applied to understand the mine accidents. The structure and concept of hazards are analyzed by Zhang et al. who divides them into root, state, material, nonmaterial, category I and II, inherent, triggering, and changing hazards [39]. Wu et al. classify the categories of the dangerous sources as accidental discharge of energy and dangerous substance in system; unsafe elements due to invalid function and the enterprise safety decisions, organizational mistakes, organizers' unsafe actions and mistakes [40]. Fan and Lu study the relation between hazard and accidents, by analyzing three components of hazards as hazard element, initiating mechanism and target and thread [41].

Hazard assessment is essential prior to any risk analysis. It should be performed quantitatively for developing a quantitative risk assessment analysis, which provides objective risk assessment. However, in most of the existing studies, hazard assessment is directed towards specific accident types. In order to assess risks

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related to accidents that are resultant from individual, occupational and locational aspects, hazards need to be analyzed considering these factors. In this paper, to capture the impact of hazards in coal mines, the hazard types are classified according to individual, operational and locational aspects. The hazards related to these categories are quantified by conducting contingency tables analyses and by using the conditional and total probability theorems. In order to implement the proposed approach, the underground coal mines (Armutcuk, Amasra, Uzulmez, Karadon, Kozlu) in Zonguldak Coal Basin in Turkey are taken into account. Experiencing high frequency and high causalities, the coal mines in the basin require risk assessment for managing the accident related risks. The lower and upper boundaries in the likelihood of defined hazard classifications are determined through event tree approach. The accidents recorded in coal mines between years 2000 and 2014 are utilized and analyzed with respect to the number, type and location of accidents, age, experience, education level and main duty of the casualties. The outcomes of this analyses are expected to detect the most and the least critical factors contributing to the risk of coal mining processes. Moreover, the proposed approach allows decision makers and regulators for better mitigating the coal mine accidents risks by identifying the most influential hazard category.

2. Overview of coal mining in the Zonguldak Coal Basin

As energy source, coal, is the second energy source after natural gas in primary energy supply of Turkey having 29% share among all available energy sources. A state owned organization, Turkish Hardcoal Enterprises (Turkiye Taskomuru Kurumu, TTK), which is responsible for the operation and administration of all hard coal activities in Turkey conducts and controls the coal production in five different underground mines, namely Amasra, Armutcuk, Karadon, Kozlu and Uzulmez mines.

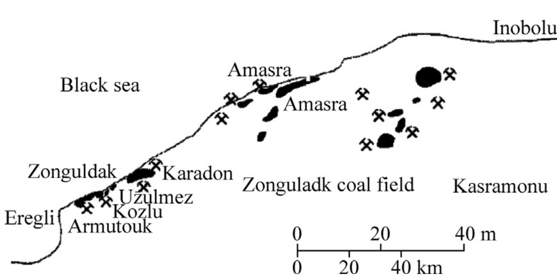


Fig. 1. Location of the mines in Zonguldak Coal Basin [43].

The structural geology of the Zonguldak Coal Basin is very complex due to existence of various faults, anticlines and synclines [27]. The locations of each mine in the Zonguldak Coal Basin are illustrated in Fig. 1. The longwall mining method is applied in all of the five mines of the basin. Changing roof and floor conditions and the dip of the coal seams make the working conditions difficult especially for some of the mines like Karadon Mine. The thickness of the coal seams ranges from 1.5 to 9 m in the coal basin. The 9 m seam thickness in Armutcuk is higher than that of other mines. The elevation of the coal seams changes between −100 and −560 m in Zonguldak Basin [42].

The total hard coal reserve of the region is 1.3 billion tonnes (t). The amount of proven reserve in the region is about 500 million tonnes and 7.5 million tonnes of coal is ready for production as of February 2016 (Table 1). Amasra and Karadon mines are two mines having the highest hard coal reserves of 406 and 409 million tonnes of coal, respectively. There is only 32 million tonnes of hard coal reserve in Armutcuk Mine and the amount of coal reserve in Uzulmez Mine is 303 million tonnes (Table 1).

The Run of Mine (ROM) coal production is the highest in Karadon, whereas Amasra yields the lowest average ROM coal per year (Table 2). The Karadon mine has the highest injury and fatality rates (Table 2). Amasra and Armutcuk mines are the two ones having relatively low annual injury rates (Table 2). Additionally, Amasra and Kozlu mines have the highest annual labor productivity as compared to the others (Table 2).

3. Analyses of accidents for the Zonguldak Coal Basin mines

The data source is the official records of TTK, which includes sweeping details for each accident such as the type, location and consequence (injury/fatality) of the accident, and personnel information, that is, the name, surname, birthday, main duty and education level of casualty, assigned duty to the casualty and the job done during the accident, injured body parts due to the accidents, brief explanation about the occurrence of the accident, starting date of employment and required absence days of the casualty (days lost). The data is collected for years between 2000 and 2014. All analyses are carried out only for the underground mine accidents. The accidents occurred on the surface and the accidents with fatality are excluded so that the impact of injuries on underground mine performance and productivity can be explained. The data set which shows variation with respect to years and the mine, is evaluated by using normalization. The analyses are performed with respect to the hazard categories over original and normalized data. The interaction between certain variables is investigated by using paired tests which leads us to determine the conditional

Table 1
Coal reserves in the region (1000 tonnes) [1].

Possible	7883	121,535	74,020	119,034	47,975	370,447
Probable	15,860	115,052	94,342	159,162	40,539	424,955
Proven	6875	169,015	134,508	129,184	64,276	503,858
Ready for production	1580	424	399	2366	2795	7564
Total	32,197	406,026	303,269	409,747	155,585	1,306,824

Table 2
ROM production, productivity, injury and fatality rates in the mines.

	Average ROM production (t/year)	Average # of workers	Average productivity (t/year/worker)	Injury rate (#/year)	Fatality rate (#/year)
Amasra	244,961	761	322	273	0.33
Armutcuk	316,907	1137	279	259	0.27
Karadon	930,480	3537	263	1122	1.87
Kozlu	591,523	1838	322	504	0.87
Uzulmez	599,771	2150	279	491	1.33
TTK	2,683,643	9423	285	2649	4.67

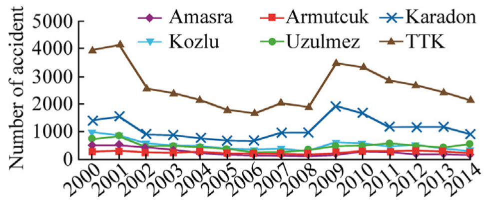


Fig. 2. Number of underground accidents in TTK mines between 2000 and 2014 [42].

association among the variables. The number, type and location of accidents, age, years of experience (experience), education level and main duty of casualties are taken as the major variables to be analyzed statistically.

3.1. Annual number of accidents

The number of accidents varies from mine to mine and also from year to year. During fifteen-year period totally 39,738 accidents are observed in the underground mines of the TTK. Fig. 2 shows that the number of accidents decreases till 2006. The same trend is seen also for all the mines. A total of 3951 underground accidents occurred in 2000, which declines to 1668 in the following six years. Between 2006 and 2008, the number of accidents fluctuates in all the mines without a significant trend of increase or decrease. However, in 2009 in all mines the number of accidents increases dramatically and reaches to a number of 3500.

Table 3 illustrates the annual number of accidents for each mine. The Karadon Mine yields the highest annual number of accidents followed by Kozlu and Uzulmez with 7569 and 7385 accidents during the fifteen years, respectively. Based on these numbers, it can be depicted that there is a rough similarity between Kozlu and Uzulmez mines and also between Amasra and Armutcuk mines. On the other hand, the Karadon mine has distinct features in terms of annual accident numbers compared to the rest of the mines in the basin (Table 3).

3.2. Type of accidents

The types of the accidents, another important factor in mine accident analysis, are categorized in seven groups referring to the earlier studies [27,44–49]. These are: roof fall, transportation, material handling, slip/fall, struck by objects, mechanical and electrical, and others. Fig. 3 and Table 4 illustrate the number of accidents falling into each of these categories over the years. It can be observed that the number of roof fall accidents leads ahead, the material handling accidents is the second common accident type. Slip/fall and struck by objects are the other accident types having relatively high shares. The distribution of the accident types varies through years which may be related with the density of different mining activities. Additionally, the same variation is observed among the mines. For example, the share of slip/fall accidents in Armutcuk is greater than that of material handling accidents. Similarly, the frequency of the accidents resulting from struck by objects is higher than frequency of material handling accidents in Kozlu and Uzulmez mines. When the distribution of accident types for each mine is examined, it is seen that the roof fall is the most important category, whereas the transportation and mechanical

Table 3
Number of underground accidents in TTK mines between 2000 and 2014 [42]

Item	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
Amasra	542	545	414	317	227	218	203	162	142	217	295	268	185	221	145	4101
Armutcuk	297	312	245	246	272	188	163	244	196	238	304	333	345	273	233	3889
Karadon	1410	1532	912	878	774	667	661	966	960	1946	1684	1177	1165	1178	917	16,827
Kozlu	950	887	570	501	442	384	354	392	264	609	590	484	488	343	298	7556
Uzulmez	752	881	444	472	445	372	287	288	352	490	488	578	521	438	557	7365
TTK	3951	4157	2585	2414	2160	1829	1668	2052	1914	3500	3361	2840	2704	2453	2150	39,738

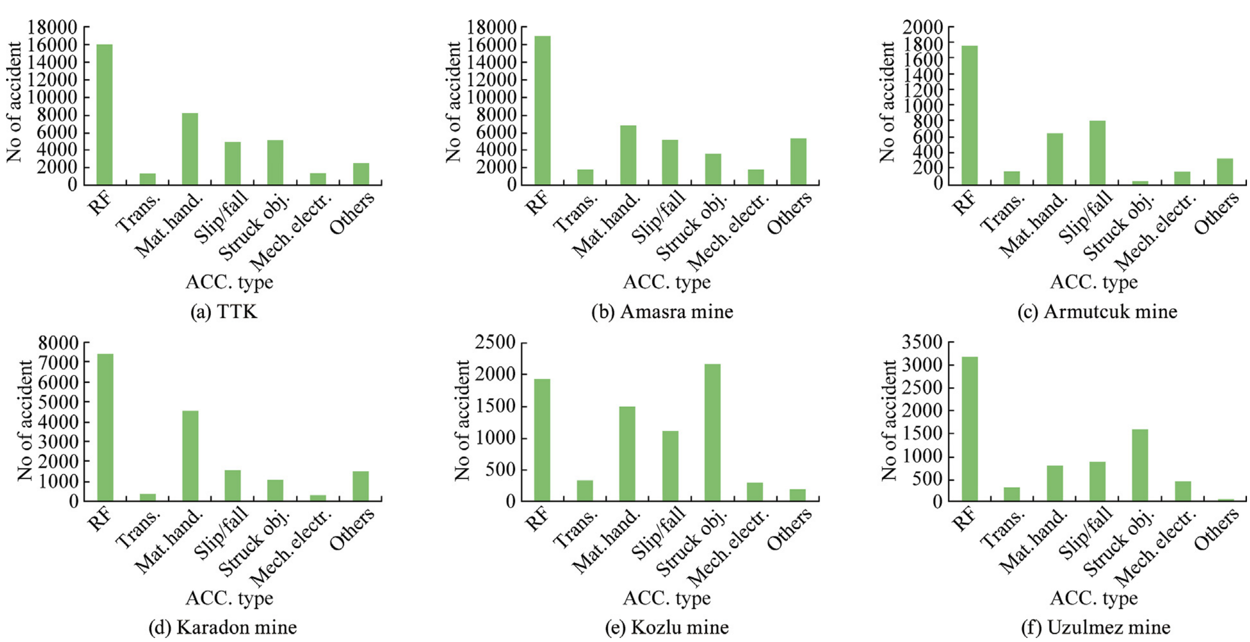


Fig. 3. Total number of accidents with respect to accident types between 2000 and 2014.

Table 4
Distribution of accidents with respect to type in TTK between 2000 and 2014.

Item	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
Roof fall	1709	1923	1169	910	852	748	652	842	765	1282	1165	1240	1232	915	598	16,002
Transport.*	155	139	75	33	72	108	40	52	68	116	132	119	111	100	90	1410
Mat. hand.*	848	806	476	509	429	374	358	353	392	853	671	561	554	503	510	8197
Slip/fall	399	434	291	310	291	248	206	273	229	403	428	331	303	396	347	4889
Struck obj.*	409	415	249	287	191	108	172	244	277	652	740	359	312	345	446	5206
Mech. electr.*	133	128	99	61	72	69	57	52	54	96	124	128	128	127	104	1432
Others	298	312	226	304	253	174	183	236	129	98	101	102	64	67	55	2602
Total	3951	4157	2585	2414	2160	1829	1668	2052	1914	3500	3361	2840	2704	2453	2150	39,738

Note: * means the transportation, material handling, struck by object, mechanical and electrical.

and electrical related accidents are the least important ones in all of the five mines (Table 4).

3.3. Location of accidents

The location of accident is one of the important factors in hazard assessment as the severity of the accidents varies accordingly. For this purpose, working places in the mines are classified into four locations in the mine and all remaining ones are classified under others category. These are production face, development face, gate road (main and tail gates), roadways and galleries (other than gate roads) and others. Table 5 shows the distribution of number of accidents with respect to location over years. The most of the accidents (22,982 accidents) in TTK appear to be in the production faces. The second highest accident frequency location is the roadways and galleries where all material and human transportation takes place. The development faces, where the opening activities of new roadways and galleries are carried out, come the third. Additionally, the frequency of occupational accidents within the chosen time frame in the development faces is in some of the years higher than that of in roadways and galleries which may be due to increasing development activities for the corresponding years.

3.4. Role of main duty in the casualties

The main duty of a worker is an important factor affecting the accident exposure, since the workers are given tasks according to their main duties. For this reason, the main duty of the casualties resulting in accidents are analyzed based on five main categories. These are production worker, development worker, transportation worker, mechanics-electrician and repairman, demontage worker, others which defines any other tasks not fitting to the defined groups. It is found that 30,010 of 39,738 casualties are the production workers located mainly in the faces and production areas (Table 6). Although the number of production workers is relatively higher than that of other workers, the portion of production worker is not as high as in the case of casualty distribution. Additionally, it can easily be seen that although the number of accidents varies from year to year, the high share of the production workers in overall distribution is the same. The number of development workers injured in the accidents (3680) comes as the second, although this is not defined so in actual main duty distribution of TTK underground workers. Table 6 points out that the number of casualties fluctuates between 2000 and 2014. However, the number of the production workers in casualties heads up to the top and the share of development worker's casualties follows production workers in all years which remains the same for each of the five mines.

3.5. Impact of age to the casualties

Since the age of workers is also an important factor in occupational accidents, the distribution of accidents with respect to the age of the causality over the years is investigated. The age groups

Table 5
Distribution of number of accidents with respect to locations in TTK between 2000 and 2014.

Item	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
Prod. face*	2474	2627	1378	1414	1274	1021	932	1319	1164	2051	1566	1521	1482	1457	1302	22,982
Dev. face*	635	618	423	402	368	438	340	300	284	242	296	253	343	265	262	5469
Gate roads	101	125	90	130	94	40	47	78	91	237	204	142	156	117	59	1711
Roadw, gall.*	447	559	564	249	238	200	208	181	227	823	1112	777	564	496	397	7042
Others	294	228	130	219	186	130	141	174	148	147	183	147	159	118	130	2534
Total	3951	4157	2585	2414	2160	1829	1668	2052	1914	3500	3361	2840	2704	2453	2150	39,738

Note: * means the production face, development face, and roadway gallery.

Table 6
Main duty of casualties in TTK between 2000 and 2014.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
Prod. W.*	2965	3195	1946	1781	1572	1223	1175	1536	1333	2948	2709	2259	2028	1824	1516	30,010
Dev. W.*	374	384	265	267	268	279	207	189	174	143	199	219	226	241	245	3680
Trans. W.*	139	151	98	88	99	120	112	130	160	166	194	149	185	184	174	2149
Mech. elect.*	114	116	84	90	82	83	69	92	120	97	104	85	100	87	70	1393
Demont. W.*	123	125	68	89	53	62	58	53	67	57	74	64	90	56	60	1099
Others	133	140	124	99	84	62	47	52	60	89	81	64	75	61	85	1256
Unknown	103	46	0	0	2	0	0	0	0	0	0	0	0	0	0	151
Total	3951	4157	2585	2414	2160	1829	1668	2052	1914	3500	3361	2840	2704	2453	2150	39,738

Note: * means production worker, development worker, transportation worker, mechanics and electronic technicians, and Demontage workers.

Table 7
Ages of casualties in TTK between 2000 and 2014.

Age	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
≤25	1183	1128	494	228	62	1	111	310	228	1031	771	387	181	75	19	6209
26–30	1383	1672	1082	1052	927	672	561	813	642	1584	1556	1225	1082	890	594	15,735
31–35	325	327	348	479	621	679	625	574	629	523	595	821	965	1038	1038	9587
36–40	664	575	350	322	237	145	135	184	257	259	356	316	354	331	380	4865
41–45	286	360	248	262	268	288	195	144	107	58	38	57	95	100	102	2608
46≤	37	65	62	67	43	44	41	27	50	45	46	34	26	18	14	619
Unknown	73	30	1	4	2	1	0	0	1	0	0	0	1	1	1	115
Total	3951	4157	2585	2414	2160	1830	1668	2052	1914	3500	3362	2840	2704	2453	2148	39,738

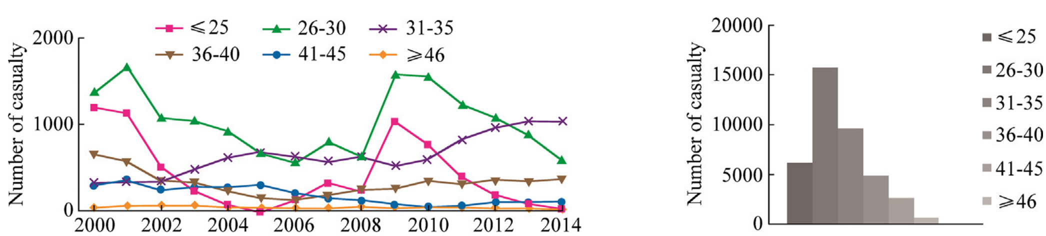
are taken as less than or equal to 25, between 26 and 30 at which the next three age intervals having an increment of 5, having the open interval of 46 and more based on the literature [10,45,49]. Additionally, an age category of unknown is allocated for the accident records whose information on the causality's age are missing. As it can be followed in Table 7, the most vulnerable group is found to be the age group 26–30 with 15,735 casualties. The second is the 31–35 with 9587 casualties followed by the workers under 25 years old. The distribution of accident numbers in each corresponding age group is similar in all the mines. On the other hand, the shares of each age group fluctuate through years. This mainly is related with the employment policies in the mines. The sharp increase in the number of casualties of younger than 25 years and 26–30 years old in the year 2009 is an important issue that should be taken into account (Fig. 4). This is mainly due to the over recruitment strategy followed in TTK for the year of 2009. In 2009, an extensive number of workers was employed and hence the increase in the casualties in the young age groups may be attributed to the rise in the inexperienced workers.

The reason of having similar share of each group in all mines is that the age category is an independent variable. In other words, age factor is an individual characteristics independent from the others. One interesting point is that with aging, the vulnerability of the workers in terms of being exposed to accidents decreases. In other words, the older workers are less exposed to the accidents, this may be attributed to the gained experience.

3.6. Experience level in the casualties

Accident exposure is shown to depend also on the experience [50]. In order to determine if longer work experience leads to fewer number of accidents, the years of experience (the years spent in the mine with a specific task) is grouped as: 0–1, 2–5, 6–10, 11–15, 16–20, over 21 and Unknown (unrecorded). Table 8 and Fig. 5 show that the workers having experience between 2 and 5 years are highly prone to accidents than the other groups (14,613). The second significant group is the workers with 0–1 years of experience. Therefore, it can be concluded that with increasing experience of workers the possibility of being injured by accidents in the mines of the TTK decreases.

The situation is almost the same for age distribution, which is an expected result. Age and experience are dependent on each other to some extent. The vulnerability of exposing to an accident decreases with increasing experience (Table 8, Fig. 5). However, there is a contradiction for the workers having 0–1 year of experience. This group has less share than 2–5 year group. There may be several reasons for this. First, this result may be due to the lower proportion of the corresponding group in the population of workers. Second and more probable one is that at the beginning of their work life (at least for these mines) relatively jobs that have low accident risk are assigned to the first group by their chiefs especially for 1 or 2 years. Third and the most important one is that at the beginning, the workers work with more experienced



(a) Over years (2000-2014) (b) Age groups

Fig. 4. Distribution of the ages of casualties.

Table 8
Experience of casualties in TTK between 2000 and 2014.

Years	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
0–1	2395	2801	362	1	0	2	268	890	610	2208	2178	81	8	39	59	11,902
2–5	161	176	1499	1728	1499	1261	198	1	244	512	460	2122	1940	1555	1293	14,649
6–10	509	294	169	173	93	97	878	928	885	622	584	98	134	381	384	6229
11–15	601	479	303	318	274	250	151	101	69	36	43	470	569	446	384	4494
16–20	243	364	216	151	269	197	147	104	72	64	47	29	21	7	9	1940
21≤	40	40	36	43	25	21	26	27	34	58	49	40	30	24	21	514
Unknown	2	3	0	0	0	1	0	1	0	0	0	0	2	1	0	10
Total	3951	4157	2585	2414	2160	1829	1668	2052	1914	3500	3361	2840	2704	2453	2150	39,738

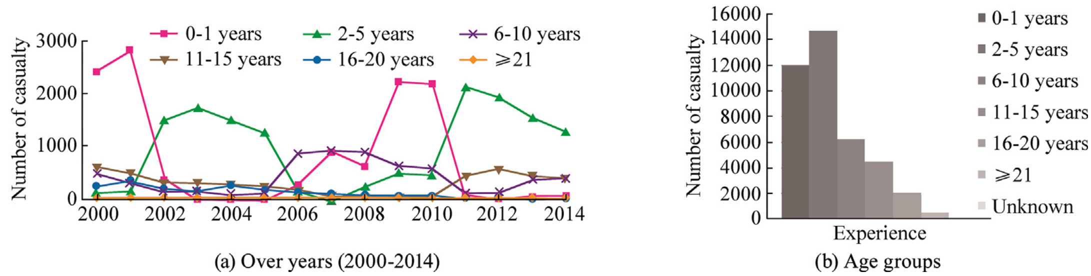


Fig. 5. Distribution of experience.

worker(s) till getting enough experience for the related job. The reason behind the high portion of accident exposure for 2–5 year group is that experienced workers may be in transition from the inexperienced period to the experienced one. The feeling of having enough experience and ignoring some safety measurements may yield to rise in accident proneness. However, after getting more than five years of experience, the probability of having accidents decreases together with increasing experience (Table 8). The sharp increase in the number of casualties having less than one year experience in 2009 has the same reasons of the age distribution (Fig. 5).

3.7. Effect of education level to the casualties

Education is important in risk mitigation and loss control in occupational accidents. Education level of workers is analyzed in five categories: primary school, secondary school, high school, university (2 or 4 years) and unknown (not recorded). Table 9 shows that in the TTK mines the majority of the casualties accumulates on the ones having primary school (25,351 cases) education. High school graduates are 7818, while the number of injured workers graduated from secondary school is 6030. The increase in the total number of accidents in the year 2009 is mainly dominated by the primary school and high school graduates.

3.8. Significance assessment tests for the defined variables

For the further steps in the proposed approach, it is critical to determine if the observed dominance of casualties in the specific groups is due to excessive number of group members or due to observed difference. The variables of “main duty”, “education level” and “age” are tested for this purpose. In order to carry out the tests, the shares of all specified variables between 2005 and 2014 for the five mines are expressed as proportions. The aggregate sum of 10 year accident data versus complete set of workers registered to the mines are compared using the t-tests. A two-sample *t*-test examines whether the considered parameters of two populations are significantly different at a level of α (usually taken as 5%) when the variances of two populations are unknown and the sample size is small. Considering the parameters as the proportions of two populations, π and p, the null (H_0) and alternative (H_1) hypotheses under a significance level of are defined as follows:

H_0: there is no difference between two proportions ($\pi = p$)
H_1: The difference between two proportions is significant ($\pi \neq p$)

where π is the proportion of the specified group in the worker population; and p the proportion of injured group in the casualty population. Tables 10–12 illustrate the *t*-test results for three vari-

Table 10
Significance tests of the variable main duty of injured workers.

Main duty	p	π	SE	t-ratio*
Production worker	0.758	0.396	0.0053	67.73
Development worker	0.087	0.105	0.0034	−5.57
Transportation worker	0.064	0.174	0.0041	−26.41
Mechanics-electronician	0.037	0.144	0.0038	−27.77
Demontage workers	0.026	0.046	0.0023	−8.75

Note: * means significant at 0.05% level.

Table 11
Significance tests of the variable age of injured workers.

Age	p	π	SE	t-ratio*
≤25	0.156	0.006	0.0009	161.53
26–30	0.396	0.081	0.0032	97.39
31–35	0.241	0.299	0.0054	−10.82
36–40	0.122	0.340	0.0056	−38.70
41–45	0.066	0.198	0.0047	−28.11
46≤	0.016	0.075	0.0031	−19.11

Note: * means significant at 0.05% level.

Table 12
Significance tests of the variable education level of injured workers.

Education level	p	π	*SE*	t-ratio*
Primary school	0.638	0.402	0.0058	40.34
Secondary school	0.152	0.212	0.0049	−12.30
High school	0.197	0.350	0.0057	−27.02
University (2 or 4 years)	0.001	0.036	0.0022	−15.76

Note: * means significant at 0.05% level.

Table 9
Education level of casualties in TTK between 2000 and 2014.

Item	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
Primary sch.	2924	3094	1947	1801	1646	1371	1159	1302	1121	1837	1808	1528	1422	1279	1112	25,351
Secondary sch.	502	523	324	333	248	230	253	327	365	616	555	501	457	423	373	6030
High sch.	423	484	297	266	258	222	244	390	402	995	944	760	789	713	631	7818
University	1	0	0	2	0	0	3	5	6	6	1	8	3	2	2	39
Unknown	101	56	17	12	8	6	9	28	20	46	53	43	33	36	32	500
Total	3951	4157	2585	2414	2160	1829	1668	2052	1914	3500	3361	2840	2704	2453	2150	39,738

Table 13
NVN (UP) in TTK between 2000 and 2014.

Item	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
Amasra	2.20	2.14	1.58	1.21	0.77	0.79	0.60	0.51	0.40	0.65	0.72	0.62	0.46	0.52	0.35	12.74
Armutcuk	1.16	1.15	0.83	0.81	0.75	0.52	0.52	0.76	0.58	0.90	1.36	1.53	1.47	1.28	1.03	13.95
Karadon	6.02	5.75	3.53	3.19	2.64	2.35	2.55	3.63	3.15	7.03	6.69	4.99	4.55	4.55	3.80	63.96
Kozlu	3.64	3.34	1.91	1.64	1.36	1.23	1.08	1.08	0.70	1.84	1.66	1.30	1.29	1.09	0.98	23.48
Uzulmez	3.27	3.61	1.57	1.65	1.39	1.32	1.19	1.00	1.24	1.72	1.60	1.90	1.77	1.56	1.71	26.41
TTK	16.36	15.98	9.36	8.45	6.88	6.16	5.94	6.83	5.94	11.99	11.50	9.76	9.08	8.69	7.61	139.53

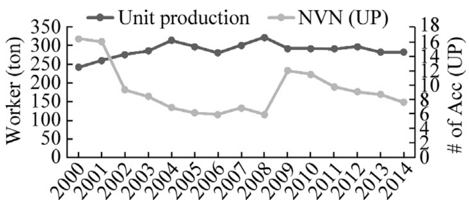


Fig. 6. Unit production and NVN (UP) in TTK.

ables, which shows significant difference (p-value <0.05) i.e., rejection of the H_0. The tests for the variable main duty illustrate that the percentage of accidents differs with respect to the specifications of the casualties. Although the proportion of production workers in overall groups (TTK) is 40%, the proportion of injured production workers in the accidents is remarkable (76%) indicating that the production workers are the most vulnerable group among the others. On the other hand, transportation workers and mechanics-electricians experienced relatively low rate of accidents (6% and 4%, respectively) relative to their percent in total worker population (17% and 14%, respectively) (Table 10). The t tests on age of casualties (Table 11) depict that there exists significant difference among age groups and the most risky group for all mines is 26–30 age group with 40% percentage of accident, even though its percentage in the worker population is 8%. The age density is found to be the highest in 36–40 age group (34%) having accident rate of 12% yielding relatively low risk. The likelihood of experiencing an accident decreases for the older workers and the vulnerability of higher age workers gets smaller as their age gets older. Regarding the t-test results for education level of casualties, Table 12 indicates that all groups in all mines are significantly different at education levels in terms of the accident rate, except the one having education level of secondary school in Uzulmez mine. Especially, primary school graduates are found to be significantly more vulnerable to occupational accidents, whereas the likelihood is smaller for other educational level groups.

3.9. Analyses of the normalized accident data

The variations with respect to geography, climate, working environment, operational systems may also have influence on the number of casualties. In order to eliminate these effects, the data is normalized and brought into a common scale. Each mine's data is normalized with respect to its unit production (UP) in order to eliminate the effect of changes or differences in the amount of (ROM) production and the number of workers (NOW) in the analysis of occupational accidents as follows:

$$NVN(UP) = N/UP \tag{1}$$

where NVN (UP) is the normalized value of number of accident/casualty with UP; N the number of accident/casualty; and UP the yearly unit production per worker (ROM production/NOW). UP is calculated for each year by dividing ROM coal production by the number of underground workers for the related year. Although the change in UP is not so significant among the mines over the years, the NVN (UP) changes apparently through the years. In 2000, the NVN (UP) is 16.36 and it decreases dramatically to 5.94 in 2008, almost a 100% jump in NVN (UP) is observed in 2009 which decreases with a low rate afterwards (Table 13 and Fig. 6).

Analyses of NVN (UP) for each mine (Fig. 7a–e) show similar pattern for overall TTK mines. UP trend is mostly stable and develops around the same values, except Amasra and Kozlu mines

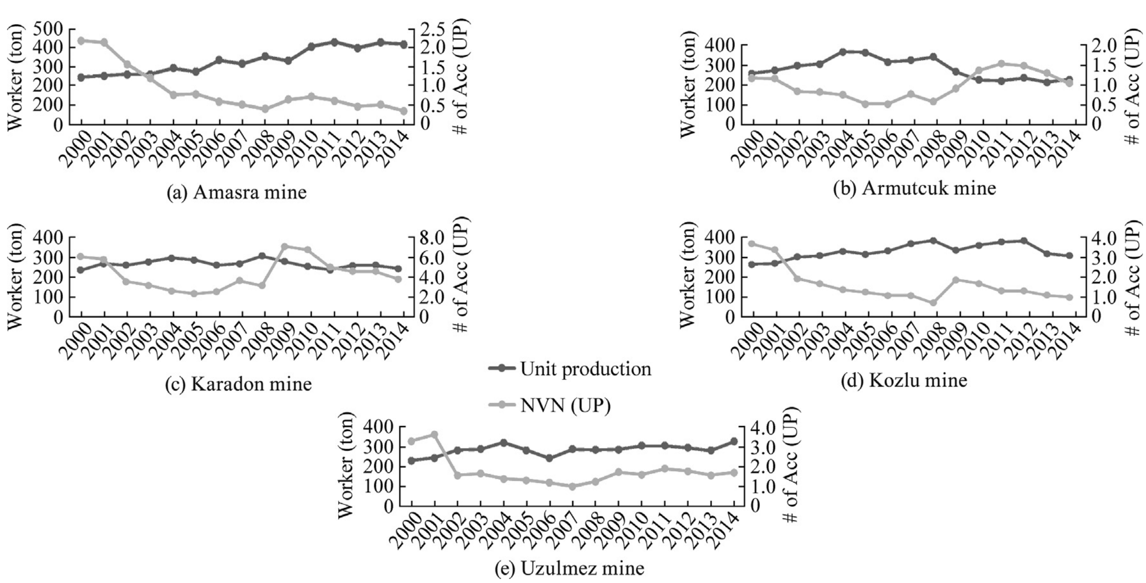


Fig. 7. Distribution of UPand NV(UP) # of accidents in each mine over years.

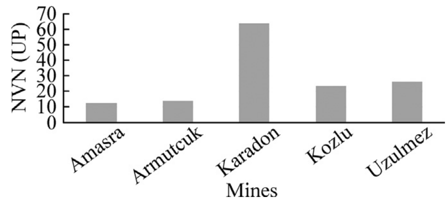


Fig. 8. Total NVN (UP in the mines between 2000 and 2014.

Table 14
Contingency tables between variables.

Type of accident	Location of accident	Experience
Location of accident	Experience	Age
Age	Age	
Experience		
Main duty		

which show an increasing trend over the years. However, the NVN (UP) exhibits a remarkable increase in 2009, whereas it is observed to be a slightly increase in Amasra and Uzulmez mines (Fig. 7a and e). In all the mines decreasing trend in NVN (UP) till 2008 is observed (Fig. 7). However, it increases in 2009 especially in Armutcuk, Karadon and Kozlu mines. To be more precise, in Amasra mine, the NV (UP)N decreases from 2.2 to 0.35 while UP increases from 250 tons/worker to more than 400 tons/worker within 15 years (Fig. 7a). Until 2008, the NVN (UP) and UP follow opposite patterns in Armutcuk Mine while number of accidents decrease with respect to the increase in production and reverses the positions by 2008 (Fig. 7b). Karadon Mine develops a similar pattern as in Armutcuk Mine till 2008, but shows a sharp increase in NVN (UP) compared to Armutcuk Mine (Fig. 7c). However, the NVN(UP) for Karadon Mine are relatively high compared to the other mines. The NVN (UP) in Kozluine has decreasing trend between 2000 and 2014 except an increase in 2009 (Fig. 7d). Moreover, the UP increases during this period. The development of these two factors in Kozlu Mine resembles to ones in Amasra Mine. Uzulmez Mine experiences a different pattern in NVN (UP). A sharp decline in 2002 remains steady with a slight increase by 2007 (Fig. 7e).

Fig. 8 summarizes the total NVN (UP) over 15 years and illustrates the variations among the mines. Karadon mine yields the highest NVN (UP) (63.96), Uzulmez and Kozlu mines follow as the second and the third with the NVN (UP) of 26.41 and 23.48, respectively. The last two ones result in the lowest NVN (UP) of 12.74 and 13.95, respectively.

4. Hazard assessment for the TTK

In mining activities, the diversity in the factors affecting hazard are many fold. Based on the accident history, the main components contributing to the frequency and the severity of the accidents are evaluated and categorized. The age, experience and main duty of casualties, type and location of the accident are considered to be the main factors which are categorized as individual (I), operational (O) and locational (L) hazards. The impact of each one is incorporated to the total hazard to assess the overall hazards due to accidents in the TTK. For this purpose, the marginal probabilities for each factor is quantified, which is followed by the determination of the conditional probabilities using the event tree analyses.

In order to quantify the hazards in marginal and conditional probabilities, first the contingency tables for factors affecting the accidents are constructed. Then, based on the results of the contingency tables, overall hazard for the TTK and each mine are assessed in terms of individual, operational and locational hazards.

4.1. Analysis of interaction between the variables

Contingency tables are utilized to determine the interaction among the variables. To determine the likelihood of each joint factor, contingency tables are obtained in bivariate relation between the variables summarized in Table 14. Tables 15–21 illustrate the probabilities associated with the joint behavior of each category listed under each factors.

The roof fall in TTK mines are the most probable occupational accidents with probability 0.403. In this sub-category the probability of roof fall in a production face is 0.287 which is the highest among all other cases (Table 15). On the other hand, the lowest probability value belongs to the mechanical and electrical accidents in gate roads with the probability of 0.001. The categories "others", and "unknown" are excluded due to unavailability of the data for each cell.

As clearly shown in Table 16, the workers within the 26–30 age group are mostly exposed to roof fall accidents with a probability of 0.175 and to the mechanical and electrical accidents the group of worker over 46 years old age group are exposed the lowest probability value of 0.001.

Similarly, the highest probability belongs to the casualties having 2–5 years of experience in roof fall accidents. On the other hand, the lowest probability value is obtained for the mechanical and electrical accidents with workers having experience of more than 21 years (Table 17).

Regarding the main duty, the injury of a production worker in a roof fall accident is the most probable event with a probability value of 0.344 (Table 18). The probability of injury of demontage workers exposed to a mechanical and electrical accident is the lowest with probability of 0.001.

Tables 19 and 20 show the probabilities of the accidents with respect to accident location, experience and age of casualties. The maximum probability belonging to the accidents in production faces with the workers having 2–5 years of experience and workers 26–30 years old are 0.239, and 0.261, respectively. On the other hand, the accidents in gate roads yield the lowest probabilities for the workers having more than 21 years of experience and workers older than 46 years old (Tables 19 and 20).

Regarding the association between age and years of experience, the maximum probability occurs for the workers having 2–5 years of experience and 26–30 years old (0.202) and the lowest probability (0.002) is obtained for the workers of 36–40 years old and having 21 or more years of experience (Table 21).

4.2. Quantification of hazard

Considering the nature of the variables and the causes, three main hazard categories are defined as mentioned before:

(1) Individual hazards, which are caused by individual characteristics of workers
(2) Operational hazards, which are related to the operational activities carried out in the mines
(3) Locational hazards, which are caused due to the mine environment like structural stability conditions.

The hazard categories and related variables are summarized in Table 22. The variables age, experience is categorized as individual hazard, operational activities such as main duty, transportation, material handling, slip/fall, mechanical and electrical and struck by objects are taken as operational hazards and accident location and roof fall are categorized under locational hazards. It should be noted that even though roof fall is a type of accident, it is highly

Table 15
Probabilities of type of the accidents with respect to the location.

Item	RF	Trans.	Mat. hand.	Slip/fall	Struck obj.	Mech. electr.	Others	Total
Production face	0.287	0.005	0.113	0.057	0.067	0.019	0.031	0.578
Development face	0.056	0.004	0.027	0.019	0.017	0.005	0.011	0.138
Gate Roads	0.004	0.007	0.010	0.009	0.010	0.001	0.002	0.043
Roadway, gallery	0.044	0.015	0.045	0.027	0.029	0.005	0.011	0.177
Others	0.012	0.005	0.012	0.011	0.008	0.005	0.010	0.064
Total	0.403	0.035	0.206	0.123	0.131	0.036	0.065	1.000

Note: Shaded values show the higher probabilities.

Table 16
Probabilities of the type of the accidents with respect to age.

Age	RF	Trans.	Mat. hand.	Slip/fall	Struck obj.	Mech. electr.	Others	Total
≤25	0.070	0.001	0.036	0.016	0.021	0.005	0.007	0.156
26-30	0.175	0.005	0.086	0.044	0.053	0.012	0.021	0.396
31-35	0.097	0.009	0.045	0.032	0.032	0.010	0.016	0.241
36-40	0.040	0.011	0.023	0.018	0.016	0.005	0.011	0.122
41-45	0.017	0.007	0.013	0.010	0.007	0.003	0.009	0.066
46≤	0.004	0.002	0.003	0.003	0.002	0.001	0.002	0.016
Unknown	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.003
Total	0.403	0.035	0.206	0.123	0.131	0.036	0.065	1.000

Note: Shaded values show the higher probabilities.

Table 17
Probabilities of the type of the accidents with respect to the years of experience.

Years	RF	Trans.	Mat. Hand.	Slip/Fall	Struck Obj.	Mech. Electr.	Others	Total
0-1 year	0.130	0.003	0.070	0.031	0.044	0.008	0.013	0.300
2-5 years	0.163	0.006	0.077	0.044	0.045	0.013	0.020	0.369
6-10 years	0.061	0.008	0.026	0.020	0.022	0.006	0.013	0.157
11-15 years	0.033	0.012	0.022	0.018	0.013	0.005	0.011	0.113
16-20 years	0.012	0.005	0.009	0.008	0.005	0.002	0.007	0.049
21≤	0.002	0.002	0.002	0.002	0.002	0.001	0.002	0.013
Unknown	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	0.403	0.035	0.206	0.123	0.131	0.036	0.065	1.000

Note: Shaded values show the higher probabilities.

Table 18
Probabilities of the type of the accidents with respect to the main duty.

	RF	Trans.	Mat. hand.	Slip/fall	Struck obj.	Mech. electr.	Others	Total
Production worker	0.344	0.008	0.161	0.083	0.101	0.023	0.036	0.755
Development W.	0.033	0.003	0.019	0.014	0.012	0.003	0.009	0.093
Transportation W.	0.004	0.017	0.008	0.008	0.007	0.002	0.008	0.054
Mechanics- Elect.	0.004	0.002	0.007	0.006	0.005	0.006	0.005	0.035
Demontage W.	0.010	0.002	0.006	0.004	0.003	0.001	0.003	0.028
Others	0.007	0.003	0.005	0.008	0.003	0.001	0.005	0.032
Unknown	0.001	0.000	0.001	0.001	0.000	0.000	0.000	0.004
Total	0.403	0.035	0.206	0.123	0.131	0.036	0.065	1.000

Note: Shaded values show the higher probabilities.

associated with the environment of mines. For this reason, it is taken into the location class.

4.2.1. Quantification of individual hazards

Since the hazard is the probability of an accident, in order to determine the hazards for the related categories, all probabilities are calculated using total probability theorem. The marginal probability of each variable and joint probability with the assumption of independence among hazard types are implemented to determine the probability of specified hazard, H_S, S = individual, operational and locational. After calculating the related hazard, the minimum and maximum specified hazards are determined for

Table 19
Probability of experience of casualties with respect to location of accidents.

0-1 year	0.205	0.026	0.009	0.055	0.005	0.300
2-5 years	0.239	0.043	0.012	0.065	0.010	0.369
6-10 years	0.081	0.030	0.009	0.023	0.014	0.157
11-15 years	0.039	0.025	0.009	0.021	0.019	0.113
16-20 years	0.013	0.011	0.004	0.010	0.012	0.049
21≤	0.002	0.002	0.001	0.003	0.004	0.013
Unknown	0.000	0.000	0.000	0.000	0.000	0.000
Total	0.578	0.138	0.043	0.177	0.064	1.000

Note: Shaded values show the higher probabilities.

Table 20
Probability of age of casualties with respect to the location of accidents.

Age	Prod. face	Dev. face	Gate roads	Roadw, gall	Other	Total
≤ 25	0.108	0.013	0.004	0.028	0.003	0.156
26-30	0.261	0.044	0.012	0.069	0.011	0.396
31-35	0.138	0.038	0.011	0.041	0.014	0.241
36-40	0.048	0.025	0.009	0.022	0.019	0.122
41-45	0.019	0.014	0.005	0.013	0.013	0.066
46≤	0.004	0.003	0.002	0.004	0.004	0.016
Unknown	0.001	0.001	0.000	0.001	0.001	0.003
Total	0.578	0.138	0.043	0.177	0.064	1.000

Note: Shaded values show the higher probabilities..

Table 21
Accident probabilities with respect to age and experience of casualties.

Years	0-1 year	2-5 years	6-10 years	11-15 years	16-20 years	21≤	Unknown	Total
≤25	0.118	0.038	0.000	0.000	0.000	0.000	0.000	0.156
26-30	0.167	0.202	0.025	0.002	0.000	0.000	0.000	0.396
31-35	0.013	0.127	0.081	0.018	0.002	0.000	0.000	0.241
36-40	0.000	0.002	0.049	0.060	0.009	0.002	0.000	0.122
41-45	0.000	0.000	0.002	0.030	0.029	0.004	0.000	0.066
46≤	0.000	0.000	0.000	0.002	0.007	0.006	0.000	0.016
Unknown	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.003
Total	0.300	0.369	0.157	0.113	0.049	0.013	0.000	1.000

Note: Shaded values show the higher probabilities.

Table 22
Hazard classification of the variables concerned.

Individual hazard	Operational hazard	Locational hazard
Age Experience	Main duty Transportation Material handling Slip/fall Mechanical and electrical Struck by objects	Accident location Roof fall

each mine. The impact of hazard is graded from weak to strong using white, light-grey and dark-grey colors, respectively. During color scaling the unknown categories are excluded in both dimensions. Additionally, each hazard group is presented in probability-tree form to illustrate the conditional association between each specific subgroups.

Individual hazard probability, H_I, requires the information on probability of age, P_{age}, and probability of years of experience, P_{exp}, depicted from contingency tables as follows:

Table 23
Individual hazards for TTK.

Age	0-1 year	2-5 years	6-10 years	11-15 years	16-20 years	21≤	Unknown
≤25	0.337	0.487	0.313	0.269	0.205	0.169	0.156
26-30	0.528	0.563	0.528	0.507	0.445	0.409	0.396
31-35	0.527	0.483	0.317	0.336	0.288	0.254	0.241
36-40	0.422	0.489	0.230	0.176	0.162	0.133	0.123
41-45	0.365	0.434	0.220	0.148	0.086	0.074	0.066
46≤	0.315	0.384	0.172	0.126	0.057	0.023	0.016
Unknown	0.302	0.371	0.160	0.116	0.050	0.015	0.003

Note: Shaded values show the higher probabilities.

Table 24
Maximum and minimum individual hazards for TTK mines.

Mine	Maximum hazard			Minimum hazard		
	Age	Experience	Likelihood	Age	Experience	Likelihood
Amasra	26-30	6-10 Years	0.530	46≤	21≤	0.020
Armutcuk	26-30	2-5 Years	0.600	46≤	21≤	0.017
Karadon	26-30	2-5 Years	0.586	46≤	21≤	0.022
Kozlu	26-30	2-5 Years	0.550	46≤	21≤	0.022
Uzulmez	26-30	2-5 Years	0.535	46≤	21≤	0.030
TTK	26-30	2-5 Years	0.563	46≤	21≤	0.023

Note: Shaded values show the higher probabilities.

$$H_I = P_{age} + P_{exp} - P_{age} \cdot P_{exp} \quad (2)$$

Table 23 shows the probability of individual hazards for the TTK at each category. The maximum and the minimum individual hazard probabilities are presented in specific details in Table 24. It is shown that the most hazard prone group is the workers between 26 and 30 age group with 2–5 years of experience in the TTK with probability of occurrence 0.563 whereas, the least one is the workers older than 46 years old with more than 21 years of experience (0.023). This is valid on mine basis except for Amasra mine which

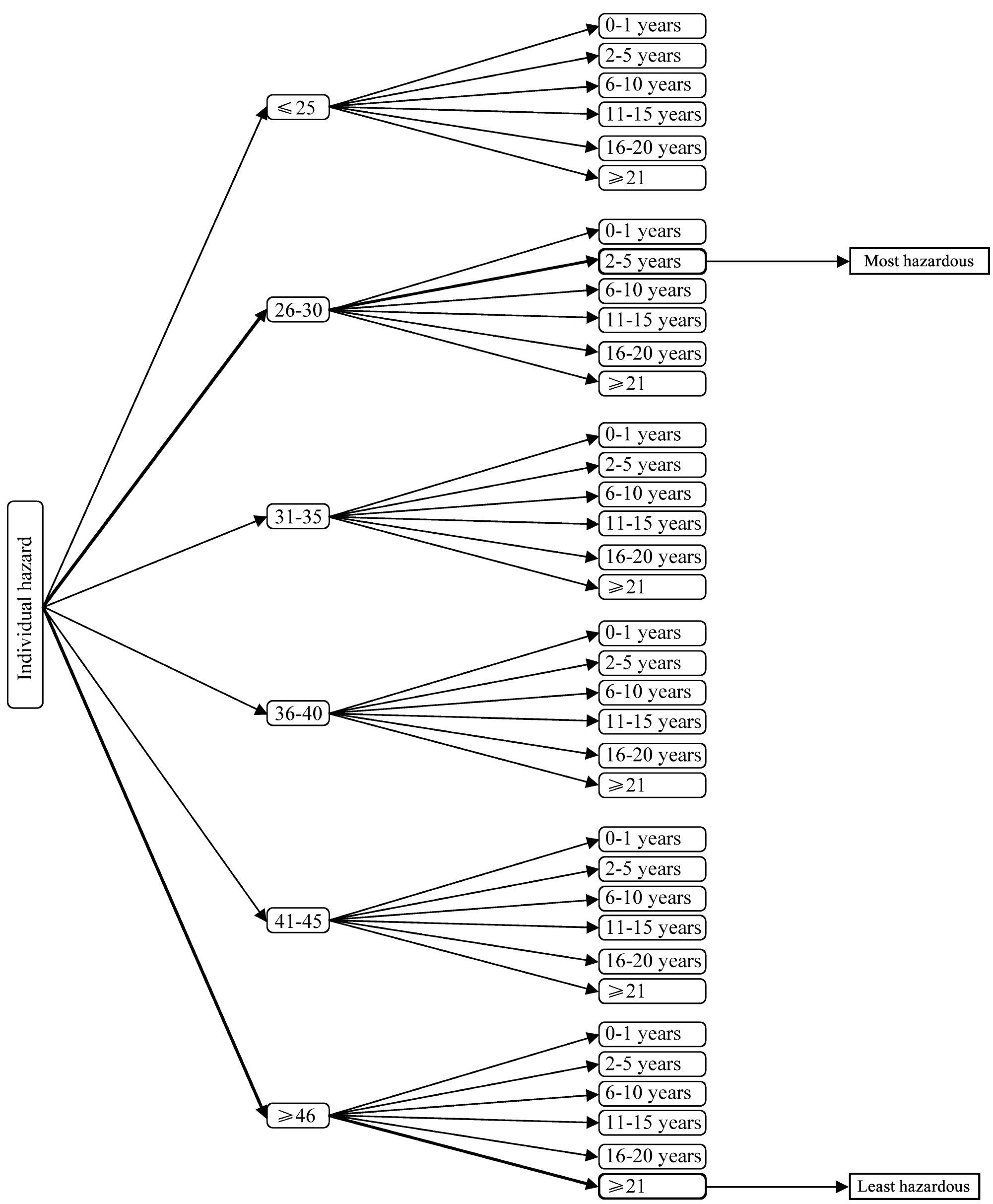


Fig. 9. Event tree of individual hazards for the TTK mines.

varies in having the maximum individual hazard probability in 26–30 age- 6–10 years of experience combination (Table 24). Concerning the lowest and the highest bivariate cases, the most hazardous mine is found to be Armutcuk mine, with workers of 26–30 years old with 2–5 years of experience (Table 24). Interestingly, the minimum individual hazard probabilities appear in the same mine with specifications age older than 46 years old and having more than 21 years of experience. In aggregate case (TTK), the minimum and maximum individual hazard probabilities imitate Armutcuk mine specifications with 0.023 and 0.563 values respectively for the same groups (Fig. 9).

4.2.2. Quantification of operational hazards

The factors like main duty, which are related to operational processes of the mining system, have considerable impact on the occurrence of the accidents. It is very often the case that the least experienced or temporary workers having less or no experience on the duty may directly or indirectly have higher proneness to accidents due to the nature of the process.

The operational hazard probability, H_O, with respect to the probability of main duty, P_{duty}, and probability of type of accident, P_{type}, is defined as:

$$H_O = P_{duty} + P_{type} - P_{duty} \times P_{type} \tag{3}$$

Table 25 illustrates that in overall picture, the highest operational hazard belongs to production workers in material handling accidents (probability 0.765) and the lowest operational hazard (probability 0.087) arises among the demontage workers experiencing accidents during transportation (Table 25). It should be noted that the roof fall is excluded since it is categorized as locational hazard. The others and unknown rows and columns are not scaled to be able to make a precise evaluation for each group.

The operational hazards with respect to each mine is listed and ranked in Table 26. It can be concluded that in terms of operational hazard, the most hazardous mine is the Karadon mine and the most hazardous group is the production workers dealing with material handling. In fact, for all the mines, production workers are the most vulnerable group while the demontage workers are the least ones in terms of operational hazards. However, the accident type changes from mine to mine depending on the operational conditions of the mines. For example, among the maximum operational hazard class, slip/fall accidents are the highest operational hazard value for the production workers in Amasra and Armutcuk mines, whereas, material handling is the most hazardous accident type for production workers in Karadon and Kozlu mines. On the other hand, struck by objects is the accident type having maximum operational hazard for production workers in Uzulmez mine. This pattern is also similar for the minimum operational hazards as illustrated in Table 26. In this categorization, the group of demontage workers struck by object accidents in Armutcuk mine has the least hazardous group among all the mines. Fig. 10 demonstrates the graphical representation of the association among operational hazard components.

4.2.3. Quantification of locational hazards

In all the mines, the most probable accident locations are production faces. Since all the other accident types are taken into account in operational hazards, roof fall accidents refer to accident type in this classification and roof fall and location of accidents are analyzed under locational hazards. It can be seen from Table 27, the maximum and minimum locational hazards in aggregate data points to production faces and gate roads, respectively. The event-tree representation in Fig. 11 shows the conditional probabilities evaluated for the locational hazards.

Table 25
Operational hazards for TTK.

Duty	Transportation	Material handling	Slip/fall	Struck by objects	Mechanical electrical	Others
Production	0.734	0.765	0.755	0.739	0.710	0.738
Development	0.154	0.414	0.282	0.299	0.155	0.195
Transportation	0.115	0.416	0.277	0.291	0.141	0.180
Mechanics Electrician	0.107	0.385	0.247	0.263	0.102	0.153
Demontage	0.087	0.365	0.230	0.245	0.089	0.135
Others	0.096	0.379	0.234	0.255	0.099	0.143
Unknown	0.064	0.349	0.210	0.224	0.065	0.114

Note: Shaded values show the higher probabilities.

Table 26
Maximum and minimum operational hazards for the TTK.

	Maximum hazard			Minimum hazard		
Name	Main duty	Accident type	Likelihood	Main duty	Accident type	Likelihood
Amasra	Production	Slip/fall	0.732	Demontage	Mech. electr.	0.097
Armutcuk	Production	Slip/fall	0.768	Demontage	Struck obj.	0.063
Karadon	Production	Mat. hand.	0.801	Demontage	Mech. electr.	0.071
Kozlu	Production	Mat. hand.	0.780	Demontage	Mech. electr.	0.071
Uzulmez	Production	Struck obj.	0.773	Demontage	Transportation	0.105
TTK	Production	Mat. hand.	0.765	Demontage	Transporation	0.087

Note: Shaded values show the higher probabilities.

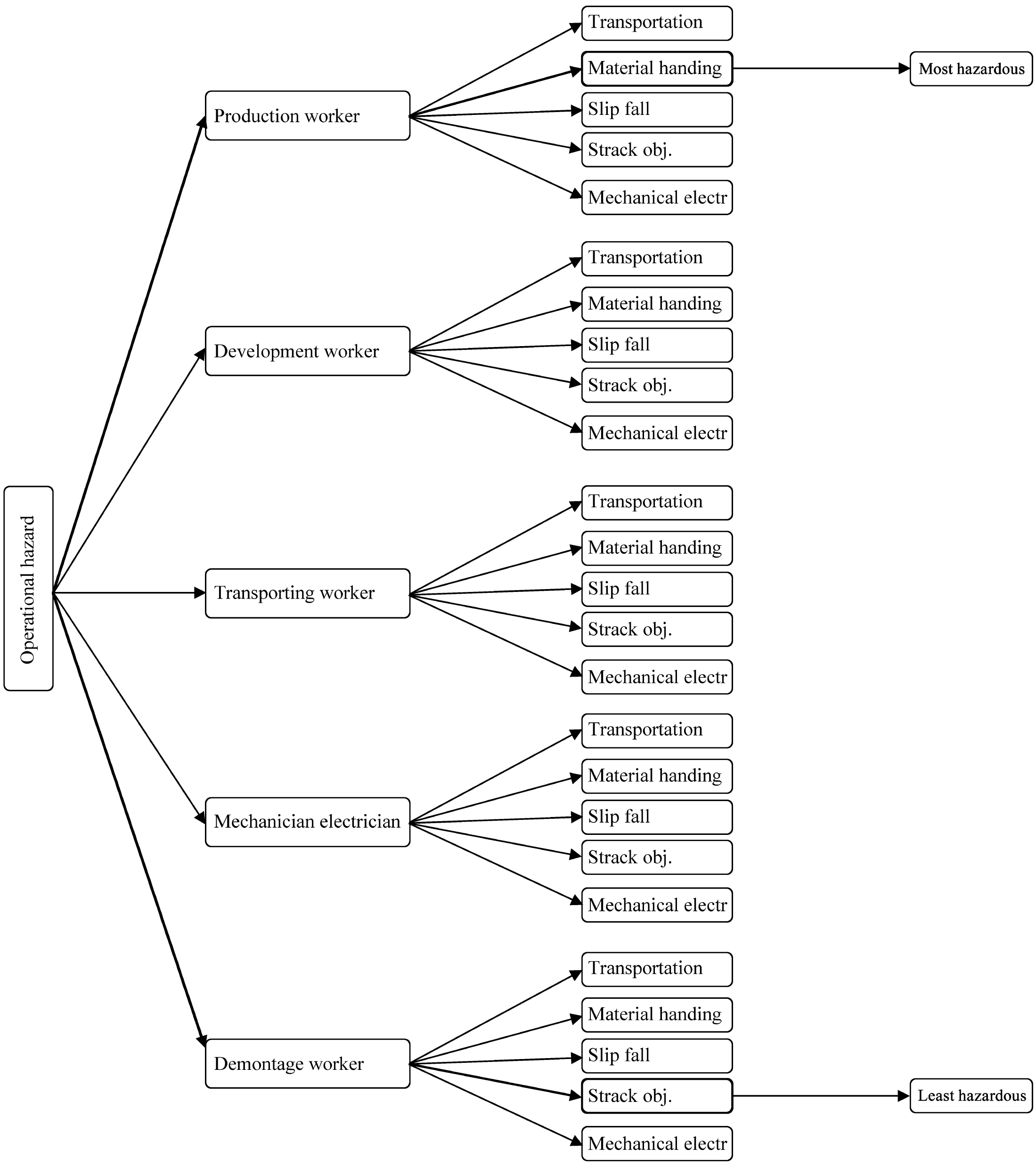


Fig. 10. Event tree of operational hazard category for the TTK Mines.

Table 27
Maximum and minimum operational hazards for the TTK Mines.

Name	Acc. location	Acc. type	Likelihood	Acc. location	Acc. type	Likelihood
Amasra	Production face	RF	0.2377	Gate roads	RF	0.0012
Armutcuk	Production face	RF	0.3739	Gate roads	RF	0.0072
Karadon	Production face	RF	0.3349	Gate roads	RF	0.0023
Kozlu	Production face	RF	0.1100	Gate roads	RF	0.0085
Uzulmez	Production face	RF	0.3381	Gate roads	RF	0.0022
TTK	Production face	RF	0.2865	Gate roads	RF	0.0038

Note: Shaded values show the higher probabilities.

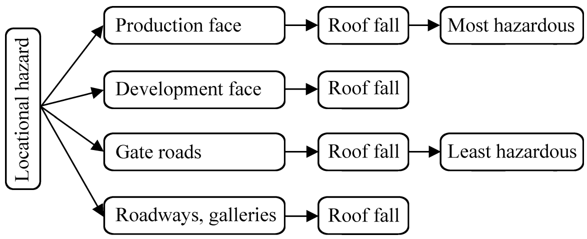


Fig. 11. Event tree of locational hazard for the TTK Mines.

Table 28
Maximum and minimum total hazard in the TTK mines.

Name	Total hazard	
	Maximum	Minimum
Amasra	0.904	0.1161
Armutcuk	0.9419	0.0852
Karadon	0.9451	0.0928
Kozlu	0.9117	0.0995
Uzulmez	0.9299	0.1335
TTK	0.9267	0.1112

Note: Shaded values show the higher probabilities.

4.3. Assessment of total hazard

Based on the determination of each component, the aggregate hazard probability (total hazard), H_T, is calculated using the total probability theorem expressed as:

$$H_T = \sum_{ijk}^{H} - \sum\sum H_{ijk} + \sum\sum\sum H_{ijk} \quad (4)$$

Considering the hazard categories, Eq. (4) becomes

$$H_T = H_I + H_O + H_L - H_I H_O - H_I H_L - H_O H_L + H_I H_O H_L \quad (5)$$

where H_I, H_O, H_L are the individual hazard, operational hazard and locational hazard, respectively. In the frame of all mines, the probabilities related to each hazard types are quantified and presented in Table 28. The maximum probabilities are all around 0.90. The Karadon mine is found to be the most hazardous mine with total hazard of 0.9451 among the others. The smallest probability of total hazard among the maximum probabilities is found to be in the Amasra Mine (0.904). Similarly, the minimum probability of total hazards come up around 0.10 at which the Armutcuk Mine yields the smallest. The Uzulmez mine has the highest hazard value. Considering the maximum total hazard values, the rank of the mines from the most and the least hazardous ones are Karadon, Armutcuk, Uzulmez, Kozlu and Amasra.

5. Conclusions

This paper aims to propose an approach for quantification of the hazards which have impact on the severity and frequency of underground mine accidents. The systematic and structured quantification of hazards are expected to generate the main component of risk assessment. The types of the hazards are categorized with respect to the ones arising from individual, operational and locational (environmental) conditions. The analysis of each factor is performed in terms of the marginal behavior of each subcomponent and then deducted to an aggregate impact of the hazards using the properties of total probability theorem. To implement the proposed approach, a case study on the data set collected from five Turkish underground mines in Zonguldak hard coal basin is taken into account. A time frame of fifteen-year accident data is processed with respect to each categories and subcategories depicted from accident history. The fatality cases are excluded and the data set is normalized with respect to unit production for each mine. Contingency tables to expose the conditional association among each category are used to determine the likelihood of each sub-hazard category, i.e., individual, operational and locational, to quantify the total hazard probability. The aggregate and mine specific analyses are performed to find the weakest (maximum) and the strongest (minimum) factors leading to the accidents in the underground mines. Event-tree analysis is used to understand the interdependence among the variables and sub-categories.

Being one of the high rate of accident occurrence rate, analyses and implementation on Turkish data give important information on reducing and mitigating the underground mine accidents in Turkey. These results are expected to guide decision makers, regulators and managers to re-structure the system according to the findings, which are listed specific to the five TKK mines as follows:

(1) The workers which are in the age group of 26–30 years with 2–5 years of experience, working in production faces should be focused to decrease their accident proneness, as they have the highest hazard values,
(2) The roof stability systems in production faces should be improved since roof falls in the production faces have the highest hazard rate,
(3) The improvement in the safety conditions of Amasra mine should be further investigated as it has the least hazard values. This is also valid for Karadon mine. Further detailed analysis should be performed in order to find the reasons for the conditions getting worse in terms of safety performance.

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