



Research Article

Investigation of issues affecting thermal comfort in water system underfloor heating applications of buildings with Bayesian networks

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ABSTRACT

Thermal comfort is related to the stability of the ambient temperature. Constant changes in ambient temperature appear as a situation that negatively affects comfort. The selected building systems must be arranged to maintain this stability for the continuity of thermal comfort. In this study, issues affecting thermal comfort in water system underfloor heating applications of buildings are handled and analyzed using the Bayesian Network modeling methodology. Visual examples of the problems encountered in field applications are also given. Three different scenarios are tested with the constructed Bayesian Network model. In the first scenario, assumed that mechanical project failures were prevented. In this case, it was observed that the failure rate decreased by about 5%. In the second scenario, assumed that mechanical application failures are prevented along with mechanical project failures. The failure rate decreased by 11% compared to the first situation. The third scenario assumed that the mechanical project preparation phase was concluded without any problems, the mechanical project was implemented without any failures, and the mechanical system was commissioned without any problems. In the last scenario, the failure rate decreased by 14% compared to the first case, and the probability of not providing thermal comfort remained at 2%. As a result of these three scenarios, the possibility of not providing thermal comfort in the underfloor heating system is detailed and interpreted.

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INTRODUCTION

Heating installations are systems established to meet the heat loss from the existing environment to another to keep the places heated at the desired temperature. Heating

systems can be grouped under two main headings, centrally and individually. If the system uses a central boiler or heater to heat the fluid (water, air, or steam), it is called a central heating system. This system uses piping to distribute the

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heated fluid and heat conductors to transfer heat to the ambient air. In central systems, the circulation pumps that pump the heated fluid into the system are not coupled to the heater device as in individual systems. Since central heating systems are high-capacity, high-flow systems, the pumps are mounted on a separate system supply group. The purpose of circulation pumps; is to ensure that the closed-circuit loop is made. In heating systems, the heated fluid must be circulated within the system. Circulation pumps realize this cycle. Since heaters such as combi boilers do not require high capacities, they contain a circulation pump and hot water storage. It does not need a separate circulation pump grouping as in central systems [1].

The system has a circulation pump that circulates the heating water. It is applied in many areas such as hotels, wedding halls, factories, public buildings, schools, hospitals, airports, health centers, fair halls, high-rise buildings, and shopping centers. If the end-users meet their heating needs individually, not from a central system, it is called an individual heating system. The difference between individual heating systems from central heating systems; Each flat or region uses its own devices, such as combi boilers as heaters. These devices have a lower capacity than large-capacity devices such as boilers. In addition, circulation pumps are usually on the device. It is used in areas with lower capacity needs, such as residences, villas, and small workplaces. Underfloor heating systems are widely preferred in buildings today to ensure uniform heat distribution in the environment. Heated air tends to rise, according to the laws of thermodynamics. In the light of this information, designing the heating systems from the area close to the ground is one of the important criteria for providing thermal comfort. Solving the heating system as a floor heating application is one of the ideal methods to achieve thermal comfort. The problems to be experienced in the processes leading to the underfloor heating application can be encountered as the inability to provide the desired thermal comfort to the end users [2,3].

In the study, the issues that effect the thermal comfort to be not provided in the water system floor heating applications were examined, and BN model compared the factors affecting the thermal comfort. Problems in thermal comfort cause people to be affected physically and mentally. Providing thermal comfort in working environments will increase the employees' productivity and lead to better quality work results.

The literature handles thermal comfort from different perspectives [4-12]. While in [4], the individual difference in thermal comfort is reviewed, [6] investigates thermal comfort in hospitals. The relationship between thermal comfort and building control research is comprehensively handled [9]. Studies of [7-9, 11-12] focus on building thermal comfort in general with state-of-the art literature reviews. In [10], the thermal comfort of educational buildings is analyzed. The literature also highlights the usage and application of BNs regarding thermal comfort topics.

Khaleel et al. [12] conducted numerical and experimental studies using parameters such as indoor air movement and temperature distribution to increase the building occupants' thermal comfort. It has been found that there is a close relationship between thermal comfort and the opening position of the exhaust. Alam and Salve [13] The parameters that will affect the thermal comfort of the people in the kitchen have been examined in detail by dividing them into two groups environmental and personal factors. Aufferberg et al. [15] presented a personalized thermal comfort model using a BN. Also They analyze the causal relationships between thermal comfort and the related factors, Aoki et al. [16] proposed a BN model. In [17], time-dependent variations in personal thermal comfort are studied via a dynamic BN. Similarly, evaluation of building design and its consequences for employee performance and operational costs is handled under a BN approach in [18]. When the studies dealing with thermal comfort are examined, it is seen that most of the studies examine the parameters affecting thermal comfort. Although the studies that deal with thermal comfort and Bayesian networks (BN) are quite limited, the study presents different scenario analyses for different situations that deal with the mechanical application, automation system, construction system, start-up defects, and mechanical project failure affect thermal comfort together in detail. In this respect, the study will enrich the literature. This paper investigates thermal comfort in the water system underfloor heating applications of buildings using a BN model. Modeling and scenario analysis were performed in GeNIe 2.4, a software for building graphical decision-theoretic BN models.

THEORY

BN is a causal inference model that aims to express uncertainties using a set of conditional events, similar to human cognitive thinking [19]. Bayesian networks are one type of graphical models containing probability distributions. This graph consists of nodes and arcs. Nodes represent random variables, while arcs represent causal relationships between nodes [20].

BN is used extensively for causal inference and discrimination and to support decision-making systems. the joint probability can be expressed as Eq. (1) [19]

$$P(u) = P(X_1, X_2, \dots, X_n) = \prod_{i=1}^n P X_i \pi(X_i) \quad (1)$$

Where X_i represent parent nodes. The marginal probability of X_i

$$P(X_i) = \sum_{1,2,\dots,(i-1)} P(u) \quad (2)$$

Assuming the known evidence α , then Eq. (3)

$$P(U|\alpha) = \frac{P(U, \alpha)}{P(\alpha)} = \frac{P(U, \alpha)}{\sum_u P(U, \alpha)} \quad (3)$$

The conditional independent relationships of a Bayesian network are expressed as follows: a node is independent of its ancestors given its parents, where the ancestor/parent relationship is to some fixed topological ordering of the nodes [21,22].

SYSTEM DESCRIPTION

The underfloor heating system is a heating system that distributes the energy it receives from the heat source with pipes in the floor screed concrete by spreading it under the floor and heating the floor and environment. The sample system diagram of the heating system is shown in Figure 1.

The required heating in the system is provided by the water of 40-50°C passing through the pipe. Homogeneous heat distribution is ensured since the underfloor heating system is distributed equally. There is almost no temperature difference between the zones. Heat accumulation on the ceiling seen in classical heating systems is out of the question for this system. Since the heat is stored in the building construction elements, the thermal comfort is not affected much by sudden temperature changes.

The heat radiates from a whole floor area in the system, and homogeneous heat distribution is provided in the

room, providing the most suitable and economical heating for human structure. While the boiler water temperature must reach 70-90°C to provide the appropriate room temperature in radiator systems, the boiler water temperature is maximum 50°C in underfloor heating systems. In radiator heating, the temperature of the radiator panels reaches 55°C, while the floor temperature is around 28°C for comfortable heating in underfloor heating systems. Figure 1 shows the current network.

Hot air zones occur near the ceiling and heater areas in the radiator system. In the underfloor heating system, it has been prevented. So up to 30%, energy savings can be provided. A comfortable environment is provided thanks to the homogeneous temperature distribution in both horizontal and vertical axis in a space with underfloor heating. All parts of the room are heated equally. In addition, since there are no radiators, it is an architecturally desirable situation.

The automation-controlled floor heating system transmits the heat energy from the main heater to the floor heating collectors through pipes. Circulation pumps ensure that the hot water circulates through the system and reaches the heater again after it cools. The water temperature coming to the collectors does not decrease. The determined hot water supply line temperature is controlled with the help of automation system equipment and automation-controlled valves. The valves on the collectors can turn the heating

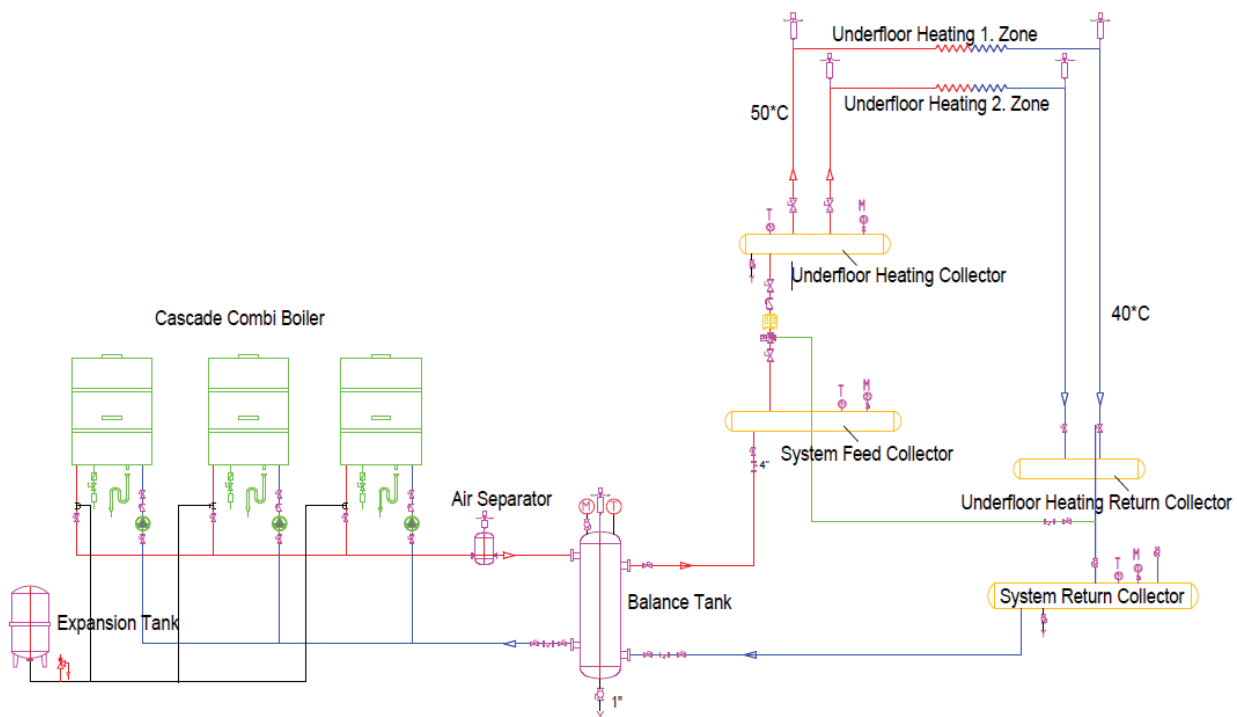


Figure 1. Heating system flow chart.

on and off in the desired areas. These opening and closing operations are made automatically according to the desired temperature value with the help of thermostats in each area. The projects created during the system’s design phase are applied in the field during installation. All parameters affecting the system have been determined to evaluate the problems of not providing thermal comfort in underfloor heating systems.

The main nodes affecting the main event are determined as B1 (Mechanical application faults), B2 (Automation system faults), B3 (Construction system faults), B4 (Mechanical project failure), and B5 (Start-up defects). Descriptions of all nodes specified in Figure 6 are given in Table 1.

Examples of nodes given in Table 1 are presented in Figures 2, 3, 4 and 5. An example of faulty pipe welding during mechanical application is shown in Figure 2. Pipe fittings are welded into the pipe from the selected materials, and the effect of pipe welding narrows the effective pipe inner space. So flow rate can be calculated during the project phase not to be achieved, and the calculated thermal comfort will not be achieved.

The defect that occurs due to applying excessive pressure during the commissioning of the heating system is shown in Figure 3. Suppose the air accumulated in the system cannot be removed during the commissioning phase. It will damage the system equipment if the air is compressed and water is added at a pressure higher than the material

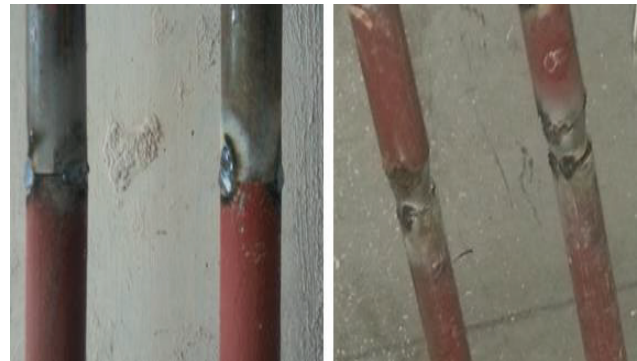


Figure 2. Application example of pipe welding fault (C3).



Figure 3. Application example of commissioning fault (B5).

Table 1. Description of failures

Node description	Node description
A1 Failure to provide thermal comfort in underfloor heating system	C14 Heat loss calculation faults
B1 Mechanical application faults	C15 Operating the system without flushing
B2 Automation system faults	C16 Incorrect installation of temperature sensing sensors
B3 Construction system faults	C17 Failure to take air accumulated in the system
B4 Mechanical project failure	D1 Use of defective welding machine
B5 Start-up defects	D2 Pipe inner diameter reduction due to welding
C1 Improper application of equipment assemblies	D3 Incorrect welding current and temperature selection
C2 Using pipe diameters different from the project	D4 Pipe welding in unsuitable climate conditions
C3 Pipe welding faults	D5 Failure to create suitable wiring for motorized valves
C4 Incorrect application of underfloor heating styrofoam	D6 Failure to select the appropriate cable cross-section
C5 Incorrect automation project application	D7 No information from room thermostat
C6 Electrical cable fault	D8 Using the floor heating screed more than the designed height
C7 Incorrect commissioning of the automation system	D9 Damage to the mechanical system by other crews in construction
C8 Incorrect application of thermal insulation	D10 Ignoring end-user requests
C9 Applied construction materials are not the same as project selections	D11 Wrong location selection
C10 Faults in construction application	D12 Use of inaccurate climate data
C11 Incorrect selection of diameters of pipes and valves	E1 Puncture of heating pipes
C12 System design parameter faults	E2 Bending of heating pipes due to impacts
C13 Wrong selection of pump capacities	



Figure 4. Application example of mechanical application fault (B1).

strength pressures. It complicates the efficient operation of the system and the water cycle. In this case, the projected calculated hot water flow will not feed the system the thermal comfort will not be at the desired levels.

In Figure 4, sample photographs of faulty applications manufactured in the field. When the mechanical system pipes and equipment are not made according to the standards, the system’s operation becomes difficult. In the photo, the compensator is deformed due to the lack of console support. An example of additional resistance to water flow is seen. In addition, due to not using air vents at the



Figure 5. Application example of construction system fault (B3).

suction cup points in heating systems, air will accumulate, and the system’s operation will be difficult. The absence of the calculated water flow rate will adversely affect thermal comfort.

Figure 5 shows Construction System Faults (B3). While the construction continues, the existing mechanical systems may be damaged. Due to these damages, mechanical system equipment may be damaged, and thermal comfort may decrease due to this damage.

Likewise, the realization rates of all intermediate nodes are given in Table 2. According to these rates, the realization rates of the main nodes B1, B2, B3, B4, B5, and the main event A1 are shown in Figure 6.

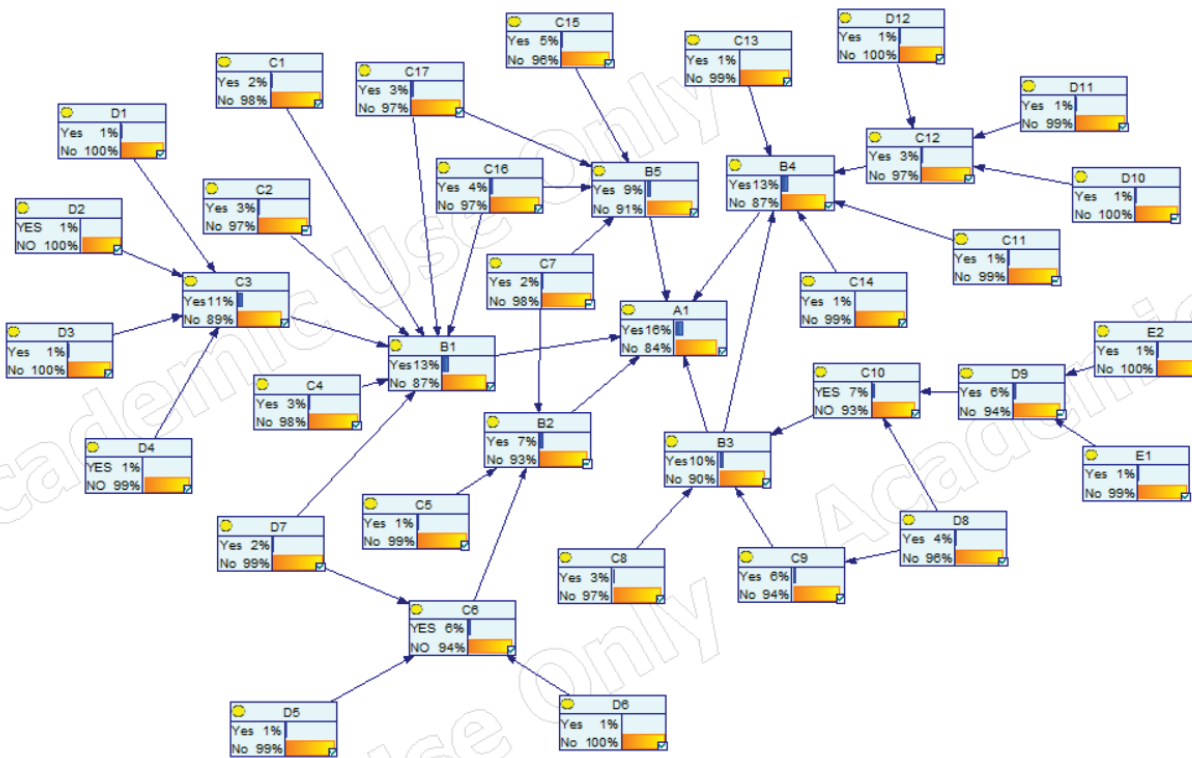


Figure 6. The constructed BN regarding the issues affecting thermal comfort in water system underfloor heating applications of buildings.

RESULTS AND DISCUSSION

Environmental factors affecting thermal comfort are temperature, humidity, and air velocity. Since underfloor heating systems are not forced-blowing systems, they do not cause discomfort for people at the point of air velocity and do not adversely affect the humidity of the environment as in radiator systems. For this reason, keeping the ambient temperature in the desired comfort conditions is important in providing thermal comfort. The failure to meet the desired conditions in thermal comfort, in general terms, can be listed as system design failures, faulty mechanical installation applications, incomplete or faulty

commissioning stages, and failures of other construction teams that will affect the mechanical system.

This study examined the effect of these factors on thermal comfort and the contribution of the improvements to the system. 37 parameters affecting thermal comfort have been determined. The causal relationships of these parameters were determined, and the BN was formed. The independent and conditional probabilities of the determined nodes are determined by considering the situations encountered in previous projects. The state of the BN and initial probabilities are presented in Table 2 and the nodes' calculated conditional probabilities and explanations are presented in Table 3.

Table 2. States of the BN and initial probabilities

Node	State	Prob.	Node	State	Prob.
D1 Use of Defective Welding Machine	Yes	0.005	D12 Use of inaccurate climate data	Yes	0.005
	No	0.995		No	0.995
D2 Pipe Inner Diameter Reduction Due to Welding	Yes	0.005	C1 Improper application of equipment assemblies	Yes	0.02
	No	0.995		No	0.98
D3 Incorrect Welding Current and Temperature Selection	Yes	0.005	C2 Using pipe diameters different from the project	Yes	0.03
	No	0.995		No	0.97
D4 Pipe Welding in Unsuitable Climate Conditions	Yes	0.01	C4 Incorrect application of underfloor heating Styrofoam	Yes	0.025
	No	0.99		No	0.975
D5 Failure to create suitable wiring for Motorized Valves	Yes	0.01	C5 Incorrect automation project application	Yes	0.01
	No	0.99		No	0.99
D6 Failure to select the appropriate cable cross-section	Yes	0.005	C7 Incorrect commissioning of the automation system	Yes	0.02
	No	0.995		No	0.98
D7 No Information from the room thermostat	Yes	0.015	C8 Incorrect application of thermal insulation	Yes	0.035
	No	0.985		No	0.965
D8 Using the floor heating screed more than the designed height	Yes	0.04	C11 Incorrect selection of diameters of pipes and valves	Yes	0.01
	No	0.96		No	0.99
E1 Puncture of heating pipes	Yes	0.01	C13 Incorrect selection of pump capacities	Yes	0.01
	No	0.99		No	0.99
E2 Bending of heating pipes due to impact	Yes	0.005	C15 Operating the system without flushing	Yes	0.045
	No	0.995		No	0.955
D10 Ignoring end-user requests	Yes	0.005	C16 Incorrect installation of temperature sensing sensors	Yes	0.035
	No	0.995		No	0.965
D11 Wrong location selection	Yes	0.01	C17 Failure to take air accumulated in the system	Yes	0.03
	No	0.99		No	0.97

Table 3. Result of Conditional Probabilities

Node	Result	Prob.	Node	Result	Prob.
B1 Mechanical Application Faults	Yes	0.13	B4 Mechanical Project Faults	Yes	0.13
	No	0.87		No	0.87
B2 Automation System Faults	Yes	0.07	B5 Start-up defects	Yes	0.09
	No	0.93		No	0.91
B3 Construction System Faults	Yes	0.10	A1 Failure to Provide Thermal Comfort in Underfloor Heating System	Yes	0.16
	No	0.90		No	0.84

Also, three different scenario analyses are performed to determine which parameters should be improved to ensure thermal comfort.

In the first scenario (Figure 7), it was assumed that mechanical project failures (B4) were prevented. Even if all system equipment is assembled on site by standards, selection failures due to system design will affect thermal comfort conditions. The scenario assumes that such failures are prevented. Thus, it has been seen that it is possible to reduce the rate of possible problems in providing the thermal comfort of the underfloor heating system after the application. In this case, thermal comfort will not be provided in 11 of every 100 projects.

In the second scenario (Figure 8), it is assumed that mechanical application failures (B1) are prevented along with mechanical project failures(B4). It has been observed that the risk to be experienced in thermal comfort has been significantly reduced with the precautions to be taken during the design of the mechanical project by the need of underfloor heating and the perfect implementation of the mechanical project on the site. In this case, 5 out of 100 projects will not provide thermal comfort.

In the third scenario (Figure 9), it is assumed that the mechanical project preparation phase (B4), which is the first stage of the mechanical works process, has been concluded without any problems, the mechanical project has been implemented without any failures in the field (B1).

The commissioning of the mechanical system (B5) has been carried out without any problems. In this case, it will be concluded that thermal comfort will be provided in 98 of 100 projects.

As shown in Figure 10, the risk of not providing thermal comfort in underfloor heating systems at the construction site is around 16%, according to experience. The scenarios have been investigated which factors can be avoided by eliminating this risk. When the assumption that mechanical project failures (B4) is prevented in scenario one is carried out, it was seen that the risk of not reaching thermal comfort decreased by 5% and reached the order of 11%. As a result of the controls to be made at the project stage before starting the application in the field, it has been seen that the project, whose calculations and technical drawings are correct, has a significant contribution to thermal comfort. The impeccable mechanical project prevents the wrong selections arising from the project from being applied incorrectly in the field. It prevents negative effects on thermal comfort. Therefore, the 5% decrease in the error rate seems reasonable. In scenario 2, it is assumed that mechanical application failures (B1) are prevented and mechanical project failures(B4). In this case, the risk of not reaching thermal comfort has decreased to 5%. We can see that the right system design and the proper mechanical application are essential in heating systems and thermal comfort. The mechanical project, which is one of

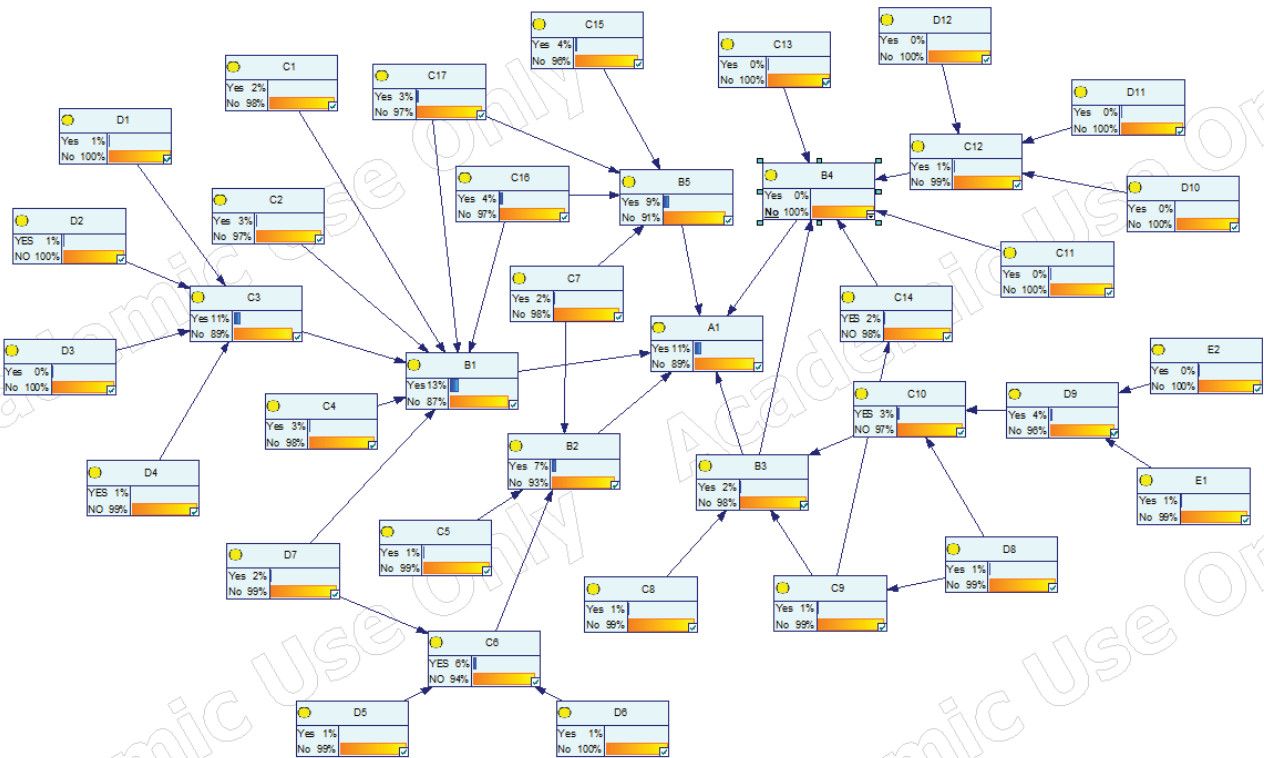


Figure 7. Failure probabilities for the first scenario (B4 is set as No).

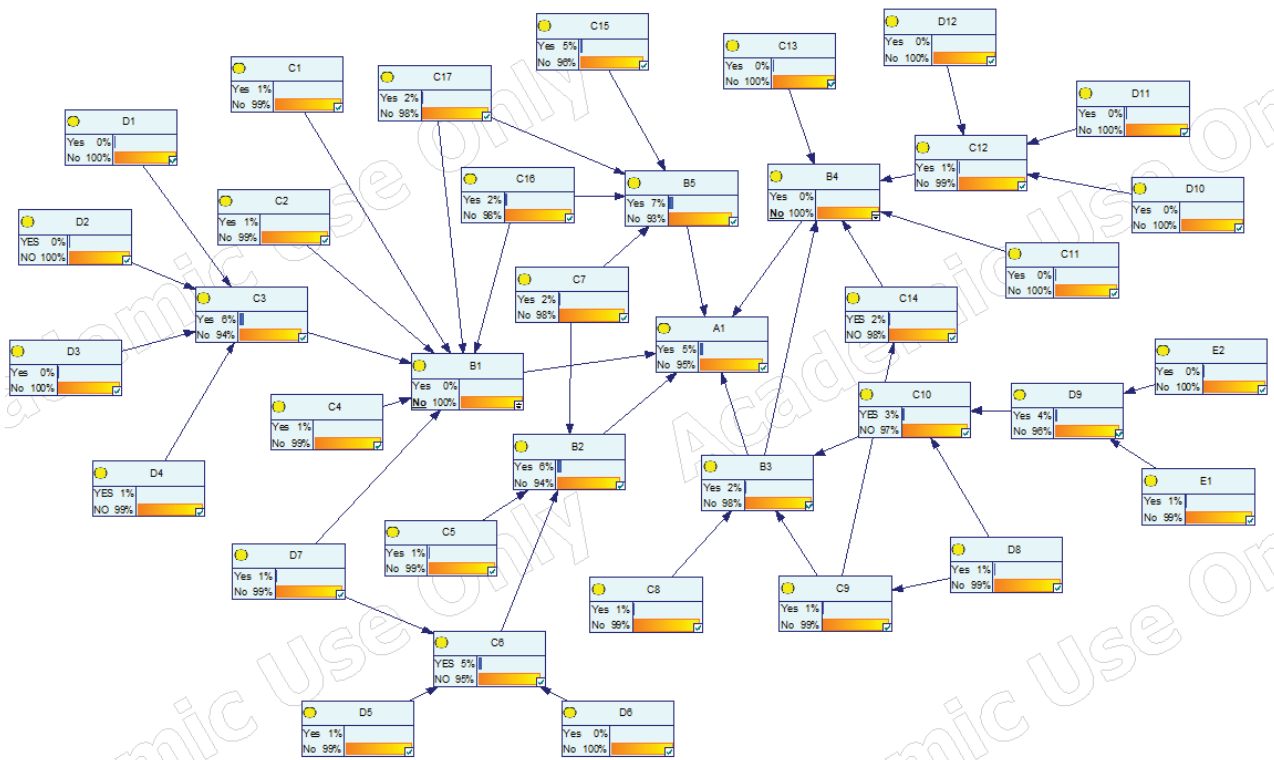


Figure 8. Failure probabilities for the second scenario. (B1 and B4 are set as No).

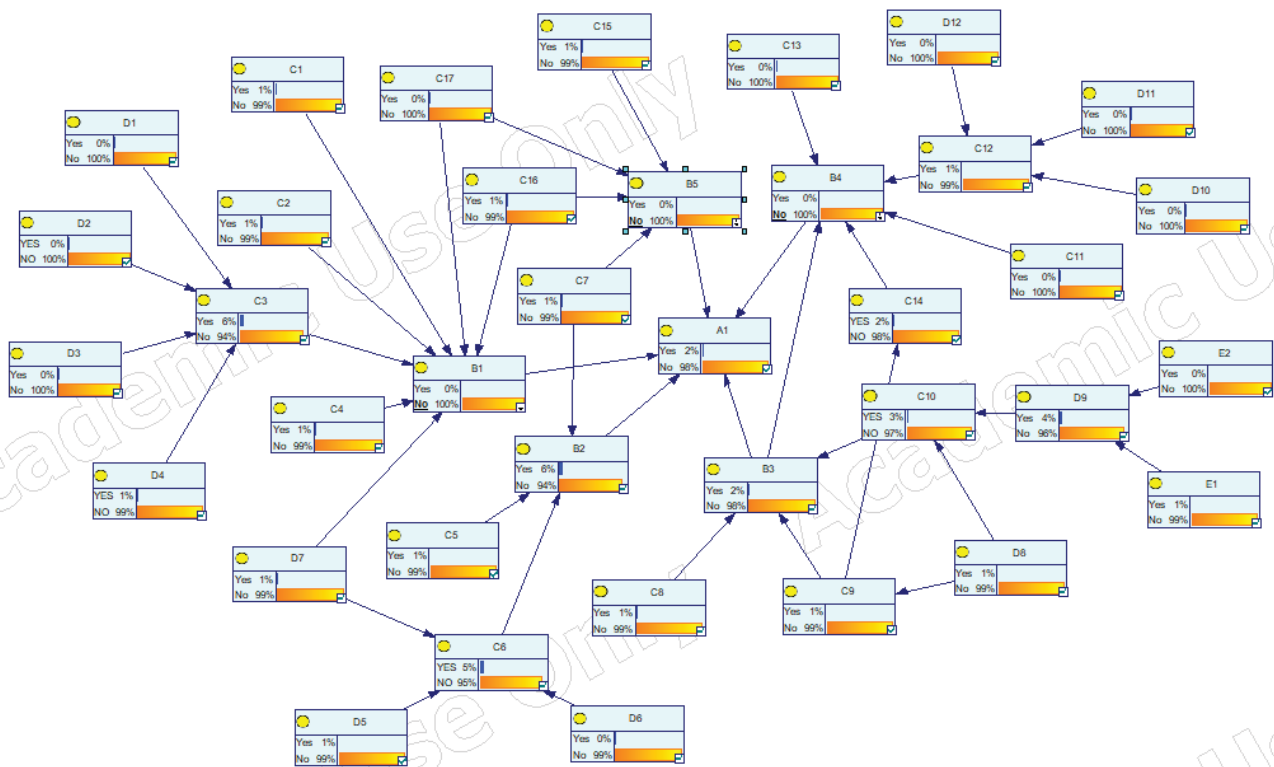


Figure 9. Failure probabilities for the third scenario. (B1, B4 and B5 are set as No).

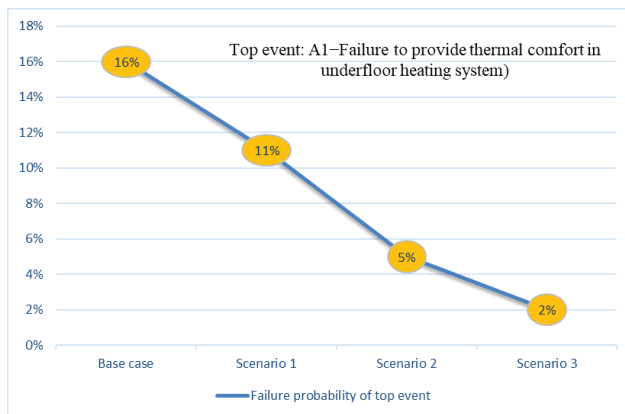


Figure 10. The realization rates of the main event according to the scenarios.

the most important factors affecting the thermal comfort, and the implementation of the project in the field is carried out without any problems, the 11% decrease in the thermal comfort according to the Bayes method reflects the realistic results. Implementing a correctly designed project with the right methods in the field will contribute to the system's efficient operation and obtain the desired result. At the point of further reducing the risk of achieving thermal comfort, it is assumed that, in addition to Scenario 2, the mechanical system (B5) is commissioning without failures. In this case (scenario 3), we see that the probability of our main event, A1 (Failure to provide thermal comfort in underfloor heating system), has decreased to 2%. When the Project-Implementation and Commissioning stages, all components of the mechanical systems, were carried out without any problems, the rate that adversely affected the thermal comfort decreased to 2%, again showing the consistency of the method. Considering the experienced sector engineers and the error rates in the examined structures, we can determine that Bayesian results make logical inferences with practice.

CONCLUSION

The need for heating has arisen from establishing a thermal balance and providing a thermal comfort environment with the heat exchange between the human body and its environment. No matter how good the architecture and durability of the building are, when the factors affecting human comfort cannot be provided, the function of the existing building will be questioned. In this respect, it is essential to provide thermal comfort in all human-oriented buildings.

Thermal comfort is defined as not feeling hot or cold in the environment where a person is, not being disturbed by the conditions he/she is in, and being satisfied with his thermal environment. The system is modeled with BN since thermal comfort is dependent on more than one parameter,

and each parameter affects each other differently. With this study, it will be possible to analyze the problems encountered in water system underfloor heating applications, the effects of these problems on the system, and the measures to be taken to provide thermal comfort. Three different scenarios were also studied in the study. The first scenario assumes that the mechanical project calculations and drawings are perfect. In this case, errors arising from system design parameters such as thermal capacity calculation, circulation pump flow rates, and pipe diameters will be eliminated, which will positively affect thermal comfort. In the second scenario, in addition to the assumption that the mechanical project calculations and drawings are prepared perfectly, it is assumed that the mechanical application is carried out perfectly in the field. Implementing the proper project on site in accordance with the project and preventing problems caused by workmanship errors will positively affect thermal comfort. While the pipe diameters given in the project are applied in the field, faulty pipe welding will be prevented, and inner pipe sections will not be narrowed. In the third scenario, in addition to the second scenario, the assumption is made that the commissioning phase of the mechanical systems is carried out perfectly. By properly evacuating the air in the system and cleaning the closed-loop system, commissioning it will positively affect thermal comfort. Especially in the third scenario, it has been observed that the thermal system comfort has improved significantly. To improve thermal comfort, mechanical application and project failures should be minimized along with commissioning.

Considering the frequency of occurrence of the mentioned failures at the construction sites, their effects on thermal comfort were evaluated. In order to provide the desired comfort in underfloor heating applications, it is necessary to ensure that the projects, whose electrical, mechanical, and automation system project calculations and drawings have been prepared perfectly, are implemented one-to-one in the field. Applications that are not made according to the project given to the field reduce the efficiency. Mistakes made during commissioning also negatively affect efficiency and thus comfort. Underfloor heating systems can provide comfort in harmony with the infrastructure on which they are built. Even if the mechanical, electrical, and automation system designs and implementations are flawless, the unsuitability of the selected materials will increase the heat loss and negatively affect the comfort. In summary, the factors that affect thermal comfort in underfloor heating systems are directly related to how accurately all sub-components specified as failure codes are applied in the study.

In this study, underfloor heating systems were taken into account. Thermal comfort evaluation has been made for floor heating, encountered in residences and villas, where comfort is more important. In this study, special structures where thermal comfort is important are considered. Thirty failures affecting thermal comfort were determined, and a

BN was created with these errors (considering the effect of each other). The probability of the main event, “Failure to provide thermal comfort in the underfloor heating system,” was determined by injecting the independent and conditional probability into the Bayesian network. Thanks to the BN, the probabilities of each error occurring one by one were determined. Thus, it was determined which error affected the main event and how much. However, as mentioned in the study, thermal comfort is important for any building. It is planned that this study will set an example for more extensive studies to be carried out for thermal comfort in the future. In future studies, considering large buildings such as hotels, shopping centers, hospitals, and business centers, incoming data can be stored by following the installation and post-delivery stages of the systems. By filtering all the information, valuable results can be obtained.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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