Visual Abstract

A review of the application of the simulated annealing algorithm in structural health monitoring (1995-2021)

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ABSTRACT. In recent years, many innovative optimization algorithms have been developed. These algorithms have been employed to solve structural damage detection problems as an inverse solution. However, traditional optimization methods such as particle swarm optimization, simulated annealing (SA), and genetic algorithm are constantly employed to detect damages in the structures. This paper reviews the application of SA in different disciplines of structural health monitoring, such as damage detection, finite element model updating, optimal sensor placement, and system identification. The methodologies, objectives, and results of publications conducted between 1995 and 2021 are analyzed. This paper also provides an in-depth discussion of different open questions and research directions in this area.

KEYWORDS. Simulated Annealing, Inverse Problem, Structural Health Monitoring, Damage Detection

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INTRODUCTION

The vital role of structures and infrastructures is undeniable in organizing voluminous human activities in large societies [1]. These structures are exposed to damage due to extreme conditions such as strong earthquakes, winds, or human-induced events [2,3]. Many structures have been constructed and are still in service despite expiration [4]. For instance, approximately 40% of bridges are more than fifty years old in the United States of America [5]. To provide structural safety and avoid human disasters and also financial losses, structural health monitoring (SHM) is a necessary procedure for civil infrastructures and structures [6]. In 2007, I35W Bridge (Mississippi, Minneapolis, USA) collapsed. Unfortunately, 13 died, and also 145 were injured. In addition, significant financial losses were imposed. This incident and similar ones could be prevented by implementing suitable SHM systems and detecting damages at their early stages [7]. Structural damage detection is the central part of SHM systems, consisting of automatic procedures for identifying and quantifying existing damages. The schematic of this process is briefly illustrated in Fig. 1. Typical damage detection strategies include three phases. In the first phase, several accelerometers measure acceleration responses. In the second phase, data acquisition systems are employed to collect data. The measured data are processed in the third phase through different damage detection and quantification algorithms [8]. It should be noted that the acceleration signals for a large-scale structure such as Milad Tower (shown in Fig. 1) are usually measured under ambient excitation [9]. Local stiffness decreases due to structural damage [10]. This stiffness loss is reflected in dynamic characteristics such as natural frequencies and mode shapes. The variation of dynamic characteristics before the damage occurrence and damaged state can be analyzed through vibration-based damage identification methodologies for detecting the damage and quantifying its extent [11]. Vibration-based methods are classified into two divisions: I) Response-based methods II) Model-based methods. Response-based methods are usually categorized as nonparametric approaches, and there is no need for finite element simulation as a baseline model. These methods typically require experimental response data and can only detect damaged elements. Response-based methods are a proper selection to establish a real-time SHM system because of their low computational cost [12]. In this regard, several signal processing techniques based on wavelet transformation and Hilbert–Huang transform have been introduced to address the structural damage detection problem more sensitively [13–18]. Model-based methods can identify both location and severity of the damaged elements. Experimental measurements and FEM of the structures are required to put model-based approaches into practice [12]. The following difficulties arise while using these techniques:

a. The numerical models should accurately represent the behavior of the structures. Therefore, developing a high-fidelity FEM of the complex structures takes considerable effort [19]. To perform a dynamic analysis [20] of Milad Tower (shown in Fig. 1), a reliable FEM is carried out by Strand7 software [21], which can be implemented in future damage detection methodologies.
b. There are some differences between the experimental results and those obtained by FEM due to the uncertainties in boundary conditions, material properties, and geometry [22]. Therefore, FEM updating is implemented as a crucial procedure to meet a good agreement between the measured and calculated modal characteristics [23]. A survey of FEM updating techniques in structural dynamics was presented by Mottershead and Friswell [24]. Recently, in 2015, another review paper in the area of FEM updating was published [25]. A comparative study of existing FEM updating methods has been conducted by Arora [26].
c. In real-world SHM projects, the size of measured degrees of freedom (DOFs) does not match the full set of DOFs of the FEM [27] because measuring the mode shapes at all DOFs is not practical, and there is no economic justification for it. To overcome incomplete measurements, either FEM reduction or mode shape expansion methods can be utilized [28]. Ghannadi and Kourehli have investigated the efficiency of different FEM reduction techniques [29]. Dinh-Cong et al. presented a comparative study of different dynamic condensation methods in detecting damages in plate-like structures [30]. Some damage detection methodologies based on expansion techniques can be found in Refs. [31–34].
d. Using complex FEM such as Milad Tower (shown in Fig. 1) is not practical for structural damage detection because of the extensive computational workload [35]. Hence, some simplified models are typically developed to represent the dynamic behavior of the structures. The simplified models can significantly reduce the computation time [36]. To detect damages, predict seismic responses, and optimize sensor locations, the FEMs of some famous structures such as Guangzhou New TV Tower [37], Shanghai Tower [36,38], MIT Green Building [39,40], and Dalian World Trade Building [41] were simplified. Pourkamali-Anaraki and Hariri-Ardebili have presented a two-step uncertainty quantification method that uses a simplified alternative model of Milad Tower [42]. The classification of vibration-based damage detection methods is illustrated in Fig. 2.

In the recent two decades, model-based structural damage identification through an iterative optimization process has received significant attention [12]. The earliest damage detection methods have been developed based on the genetic algorithm (GA) [43–45]. Dynamic characteristics such as natural frequencies and mode shapes are employed to construct an objective function when using optimization-based damage detection methods [12]. In recent years, some novel optimization algorithms have been rapidly developed. For instance, several researchers have employed moth-flame [46], salp swarm [47], multiverse [48], whale [49], YUKI [50,51], wild horse [52] and slime mold [53] algorithms to solve the inverse problem of damage detection. However, conventional optimization methods such as simulated annealing (SA), particle swarm optimization (PSO) [54], and GA are still often used in damage identification problems. During the last two decades, the application of the SA algorithm is not limited to damage detection problems but also has other functions in

terms of SHM, such as optimal sensor placement, system identification, and FEM updating. This paper presents a tabulated review of the application of the SA algorithm in the field of SHM (1995-2021). This paper investigates roughly 30 previously published studies to discuss objectives, methodologies, types of structures, and overall results of recent articles.
Some review papers in different disciplines were conducted between 1987 and 2018 (Tab. 1). The number of review papers on other fields is also depicted in Fig. 3. It can be observed that the present paper is the first review study on structural damage detection and families of SHM, such as FEM updating, system identification, and optimal sensor placement.

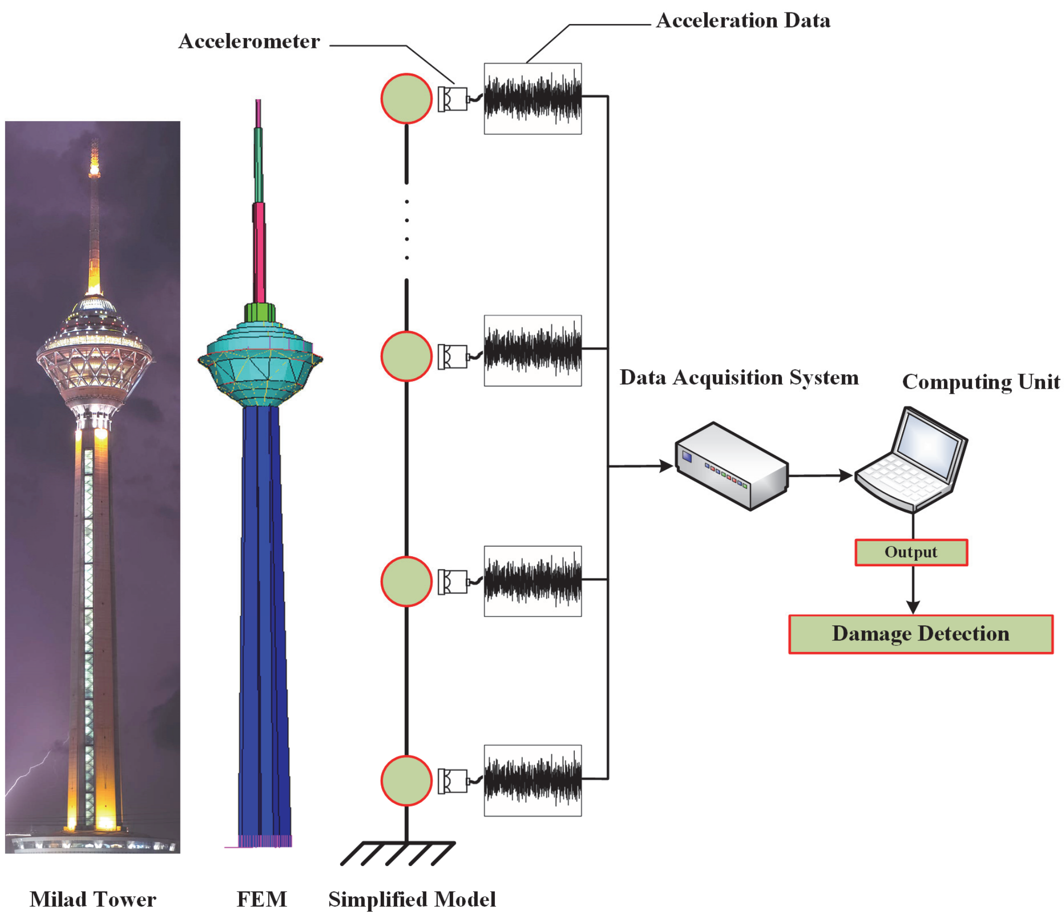


Figure 1: The schematic of vibration-based damage detection procedures (3D model courtesy of Faham Tahmasebinia).

Ref.	Year	Title
Aarts and van Laarhoven [55]	1987	Simulated annealing: a pedestrian review of the theory and some applications
Koulamas et al. [56]	1994	A survey of simulated annealing applications to operations research problems
Mavridou and Pardalos [57]	1997	Simulated annealing and genetic algorithms for the facility layout problem: A survey
Suman and Kumar [58]	2006	A survey of simulated annealing as a tool for single and multiobjective optimization
Nandhini and Kanmani [59]	2009	A survey of simulated annealing methodology for university course timetabling
Hooda and Dhingra [60]	2011	Flow shop scheduling using simulated annealing: A review
Pattanaik et al. [61]	2012	Simulated annealing based placement algorithms and research challenges: A survey
Kaushik and Ghosh [62]	2014	A survey on Optimization Approaches to K-Means Clustering using Simulated Annealing
Siddique and Adeli [63]	2016	Simulated annealing, its variants and engineering applications
Sibalija [64]	2018	Application of simulated annealing in process optimization: A review

Table 1: List of review papers on applications of SA algorithm in various fields.

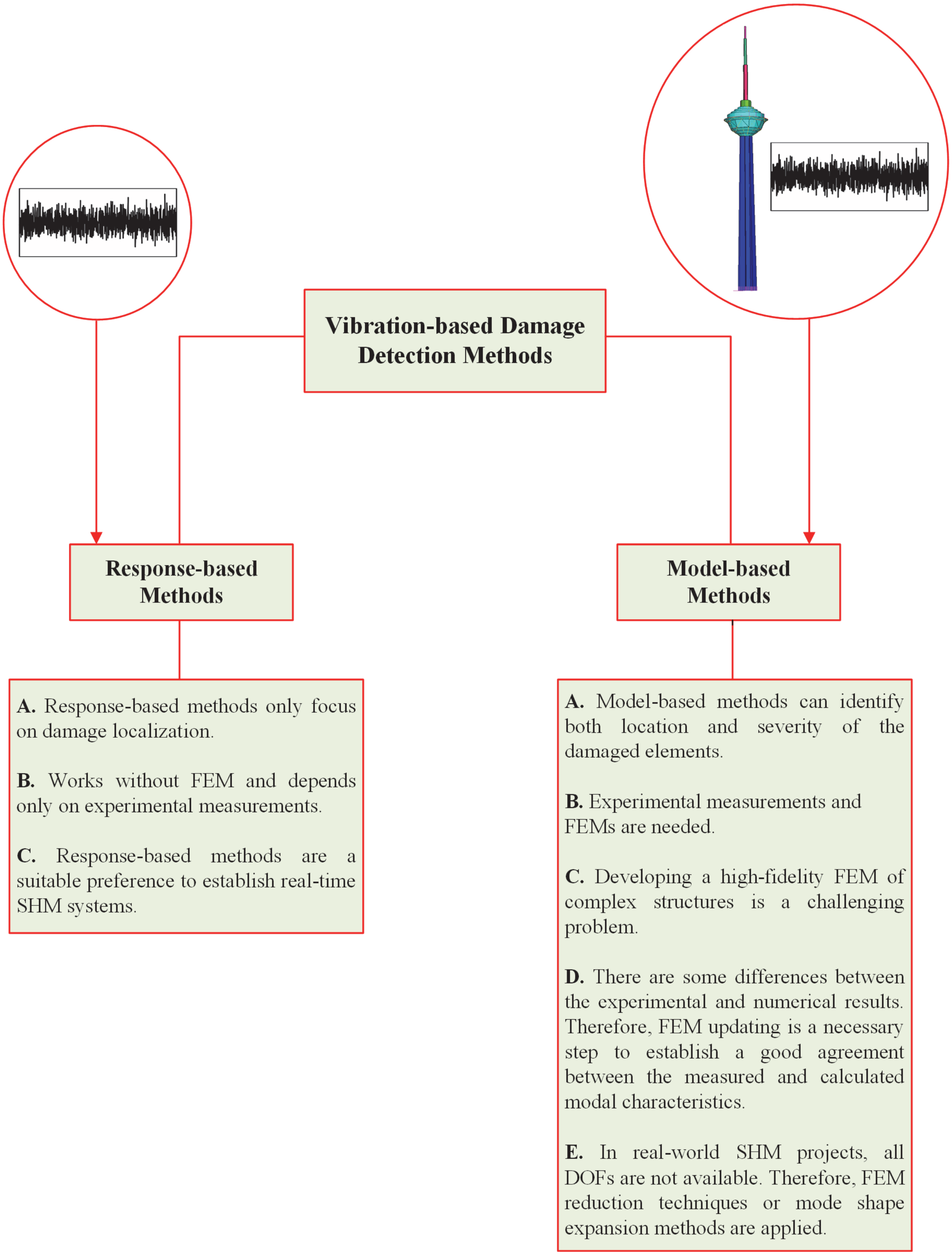


Figure 2: Classification of vibration-based damage detection methods (3D model courtesy of Faham Tahmasebinia).

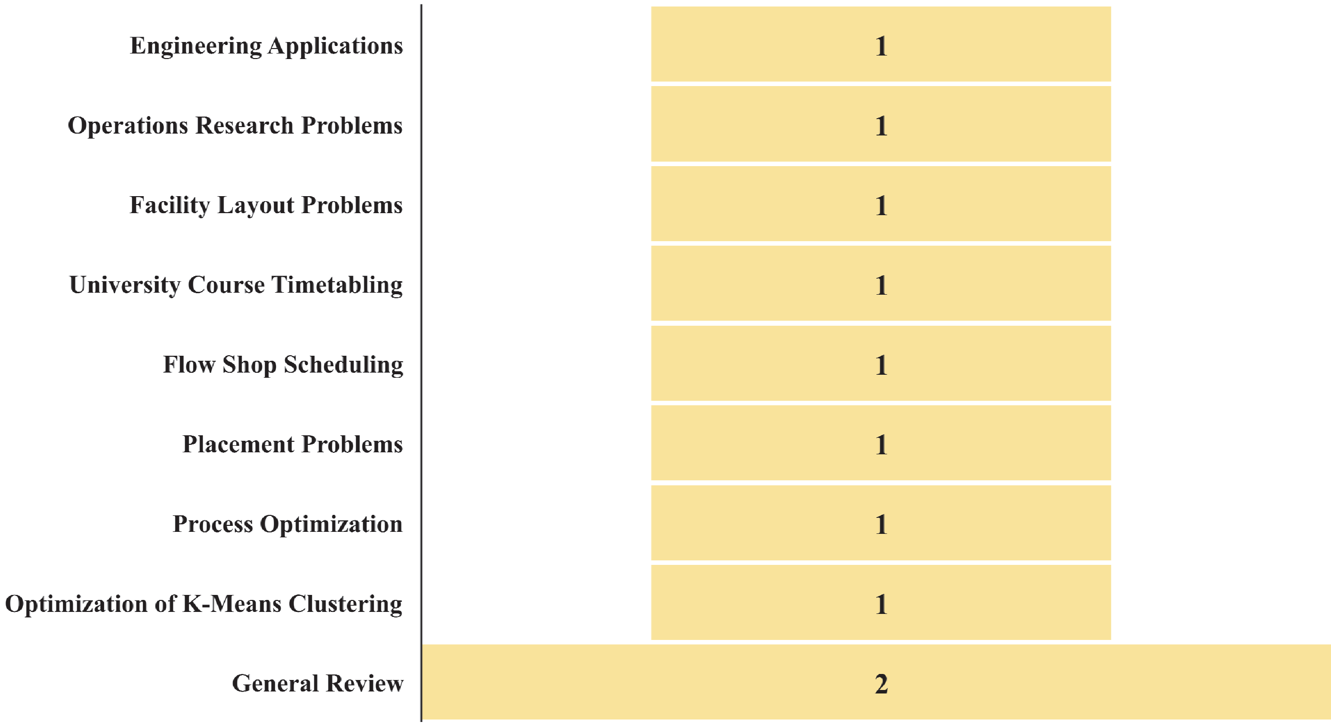


Figure 3: Number of review papers on different applications of SA.

SIMULATED ANNEALING (SA) ALGORITHM AND PROBLEM DEFINITION

The SA is a widely used optimization technique that mimics the annealing procedure of solids [65,66]. Kirkpatrick et al. [67] and Černý [68] each independently developed the SA algorithm. This procedure is a physical activity that produces high-quality materials by cooling them gradually from a high temperature [69]. Therefore, the initial solution randomly generates from a hot temperature. Then, the temperature slowly reduces, and the optimal solution achieves [65]. However, Metropolis et al. [70] introduced an algorithm for efficiently simulating the evolution of a solid to thermal equilibrium in 1953 for the first time [71]. After approximately 30 years, Kirkpatrick et al. [67] and Černý [68] realized that the optimization problems could be solved by implementing the Metropolis criterion. In other words, there is a significant analogy between minimizing the cost function of an optimization problem and the slow cooling of a solid till it reaches the ground state, which is little energy [71]. Finally, Kirkpatrick et al. [67] presented the SA algorithm by adjusting the cost for energy and performing the Metropolis algorithm at a series of gradually decreasing temperature levels [71]. The SA algorithm attempts to prevent entrapping in the local optimal solution through the Metropolis criterion and performs extra random searches in the neighborhood of the candidate solution [72]. Fig. 4 shows the flowchart of the SA algorithm. The Metropolis rule determines how a thermodynamic system changes from state X_{old} to state X_{new} [73,74]. The acceptance probability is as follows:

$$p = \begin{cases} 1 & if \quad E(X_{new}) < E(X_{old}) \\ \exp^{\left(-\frac{E(X_{new})-E(X_{old})}{T}\right)} & if \quad E(X_{new}) \geq E(X_{old}) \end{cases} \tag{1}$$

where T is the temperature, $E(X_{new})$ and $E(X_{old})$ represent the energy of the system in states X_{new} and X_{old}, respectively [65]. Different researchers have assessed the applicability of the SA algorithm to various engineering problems, especially in structural engineering. One of the earliest applications of SA related to the weight optimization of a 10-bar cantilever truss was published in 1988 [75]. In another work, Balling [76] implemented the SA for the optimal design of three-dimensional steel frames. Shim and Manoochehri [77] introduced a combinatorial optimization procedure based on the SA algorithm to generate the optimal configuration of structural members. Leite and Topping [78] studied the efficiency of the parallel version of SA in structural optimization problems. Over the past two decades, successful applications of the SA have been reported several times. For example, Bureerat and Limtragool [79], Lamberti [80], Sonmez and Tan [81], Tejani et al. [82], Kurtuluş et al. [83], Najafabadi et al. [84], and Goto et al. [85] are a few to be noted.

It is necessary to define an objective function based on measured and calculated modal characteristics to solve the model-based inverse problem of damage detection using optimization algorithms [86]. The inverse analysis using an optimization algorithm attempts to find the optimal design parameters for damage detection by minimizing the differences between the measured and calculated modal characteristics [87,88]. An inverse problem of damage detection has the following mathematical formulation [89]:

$$\begin{aligned}&\text{Find} \quad \Lambda = \{\alpha_1, \alpha_2, ..., \alpha_{Ne}\}\\&\text{Minimize} \quad f(\Lambda)\\&\text{Subject to} \quad 0 \le \alpha_e \le 1 \quad (e = 1, 2, ..., Ne)\end{aligned} \tag{2}$$

where $f(\Lambda)$ denotes the objective function, *Ne* represents the number of elements, and Λ is a vector that includes stiffness reduction coefficients [89].

The elemental mass matrix is typically assumed not to alter due to damage, and stiffness coefficients define structural damage [89,90]. If the stiffness coefficient of the *e*th element is considered to be α_e, the global stiffness matrix will be represented as the sum of the damaged and undamaged stiffness matrices [91] and can be expressed as:

$$K = \sum_{e=1}^{Ne} (1 - \alpha_e) K_e \tag{3}$$

where K_e denotes the stiffness matrix of the *e*th element and α_e is considered in the range of 0 to 1 and indicates the severity of the damage [92].

For example, one of the frequently utilized objective functions in damage detection problems is given by Eqn. (4).

$$f(\Lambda) = \sqrt{\frac{1}{m}\sum_{i=1}^{m} w \left(\frac{\omega_i^{Measured} - \omega_i^{Calculated}}{\omega_i^{Measured}} \right)^2} \tag{4}$$

where *m* represents the number of modes considered , *w* is a weighting factor, $\omega_i^{Measured}$ and $\omega_i^{Calculated}$ are the *i*th measured and calculated natural frequencies, respectively [89].

Analysis of papers on structural health monitoring using the SA algorithm (1995-2021)

The purposeless strategy for reading scientific articles is to read them like a textbook: start with the title and read through the list of references, taking in each word without any critical thought or analysis. The active reviewers should be able to identify the main structure and answer the following critical questions by skimming the article [93].

- The objective of this study - Why was it conducted?
- The methodology of this study - How was it conducted?
- The result and finding of this study - What was found?

This review paper enables the researchers to effectively comprehend the previously published papers' objectives, methodologies, and results. Tab. 2 presents a classified review of the SA algorithm's application in the context of FEM updating, system identification, optimal sensor placement, and especially structural damage detection.

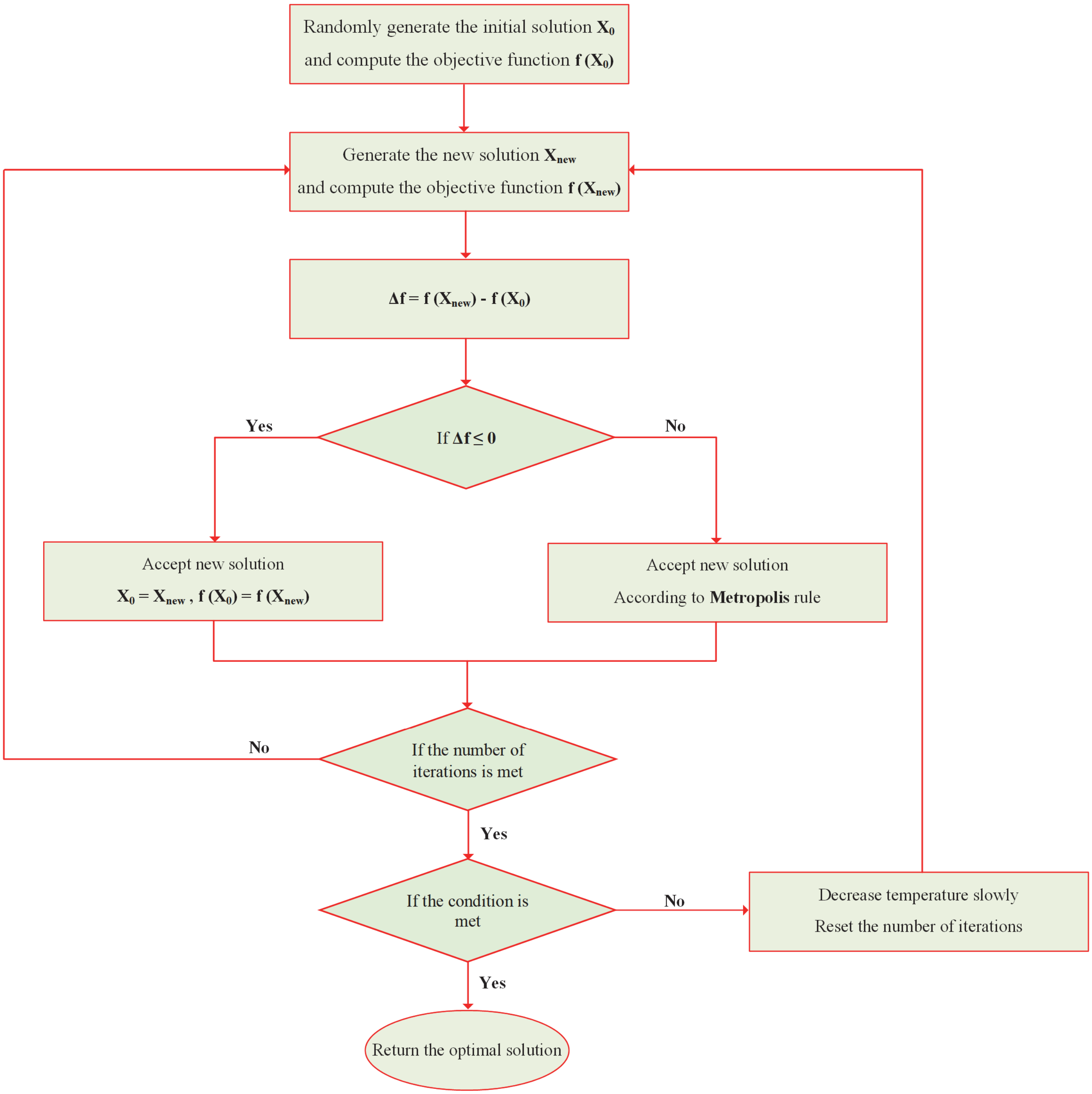


Figure 4: Flowchart of SA algorithm [65].

Ref.	Year	Objective	Methodology	Structure	Result and Finding
Keilers and Chang [94]	1995	This study presents a methodology to find the size and location of the delamination when built-in sensors are embedded in the laminated composite beams.	A variant of SA is employed to minimize the weighted quadratic objective function and establish an agreement between the calculated and measured frequency responses. Finally, the dimension of the delamination is estimated when the minimization process is over.	Laminated composite beam	This study showed the feasibility of the proposed delamination detection method based on built-in sensors, actuators, and an optimization procedure for laminated composite beams. The optimization technique is a particular variant of the SA algorithm and enables parallel searching for numerous local minima until the global minimum is discovered. However, remarkable efforts are necessary for accurate damage detection under noisy conditions.
Jeong and Lee [95]	1996	This paper introduces a hybrid method known as the adaptive simulated annealing genetic algorithm (ASAGA). GA has a low capability in hill-climbing. In the opposite state, SA very well supports probabilistic hill-climbing. Therefore, ASAGA enjoys the merits of GA and SA simultaneously. Finally, the efficiency of the hybrid algorithm is demonstrated by a system identification example. **Not:** System identification is an approach to developing a mathematical model of a dynamic system through input and output measurements [96].	ASAGA is applied to estimate the model parameters of the auto-regressive moving average with exogenous excitation (ARMAX). Then, the outcomes were compared with those obtained by GA and a gradient algorithm.	Discrete-time system	The comparative results showed that the ASAGA is superior to the GA and a gradient algorithm. Besides, ASAGA improved GA's poor hill-climbing capability and accelerated the convergence. Therefore, the combination of SA and GA provides an efficient optimization algorithm.
Levin and Lieven [97]	1998	This study proposed the blended simulated annealing algorithm (BSA) for adjusting mass and stiffness during the FEM updating procedure. For additional investigation, the performance of BSA is also compared with GA.	The optimization-based FEM updating is performed based on different objective functions in the frequency domain.	Cantilever beam Flat plate wing	It was concluded that the BSA provides better results than the GA in all examined cases. By increasing the discretization level, GA could improve the results. But the computation time increases considerably. The results of this study also clearly showed that the degree of agreement between the numerical model and experimental data depends on updating parameters. The updated model correlates sufficiently with experimental measurements when many parameters are taken. In contrast, limited updating parameters could not provide a reliable correlation.

Ref.	Year	Objective	Methodology	Structure	Result and Finding
He and Hwang [98]	2006	GA encodes variables as finite-length strings. Therefore, excessive computation time is required. A new variant of GA called the real-parameter genetic algorithm (RGA) was proposed to overcome this major drawback of GA. RGA saved much computation time by directly handling the variables without coding. However, GA is still weak in hill-climbing. A new hybrid algorithm based on SA and RGA was developed to address the low hill-climbing ability and slow convergence of GA, known as the adaptive real-parameter simulated annealing genetic algorithm (ARSAGA).	Three objective functions are defined to formulate the damage identification problem as an optimization scheme. The first one is established on the discrepancy between the calculated and measured displacements. The second objective function is based on natural frequency changes. The last is the sum of the first and second objective functions.	Curved beam Cantilever beam Clamped - Clamped beam	The results indicated that the combination of SA and RGA (ARSAGA) modifies RGA's convergence speed and searching ability. Additionally, the proposed algorithm is efficient for detecting the damages in beam-like structures with various boundary conditions, even under noisy and incomplete measurement conditions.
Marwala [99]	2007	Three optimization algorithms, including PSO, GA, and SA, are employed for FEM updating. Then, the correlation of updated mode shapes and natural frequencies is compared with corresponding measured ones. The computation time for the optimization algorithms was reported.	This study considers the modulus of elasticity as a design parameter for FEM updating. The weighted objective function relying on the relative interval between the measured and calculated natural frequency is adopted for the minimization process.	Irregular H-shaped structure	The results of this study showed superior performance of PSO in terms of correlation between measured and updated dynamic characteristics. Moreover, PSO is the fastest optimization algorithm compared to GA and SA.
He and Hwang [100]	2007	This study suggests a two-step strategy through grey relation analysis (GRA) and ARSAGA for structural damage detection. The main contribution of this study is the use of narrowed search space and a reduced number of design variables as possible damage elements.	The undamaged elements are first excluded using GRA. In the second step, ARSAGA solves the optimization problem by minimizing an objective function defined by the differences between the measured and calculated displacements. Finally, the damaged locations and their corresponding severities are determined.	Plane truss Clamped - Clamped beam	The results of this paper can be summarized as follows: I) Where the measured data includes a 5% error, the damage parameters of the clamped beam are accurately identified. II) Where there is a 5% error in the measured data, the predicted results of the plane truss are reasonable but not accurate. III) Under error-free conditions, the proposed technique efficiently identifies the damages in both structures. The GRA plays an undeniable role in this proposed damage detection strategy, as poor results are obtained if GRA is not utilized.

Ref.	Year	Objective	Methodology	Structure	Result and Finding
Jie and Aiqun [101]	2008	To have a quick convergence, auto-optimizing network topology, and to avoid being entrapped into the local minimums, the backpropagation (BP) neural networks were improved by the SA algorithm, momentum item, bold driver technology, and stochastic hill-climbing algorithm.	The learning process in modified BP neural networks avoids entrapment into the local minimums by implementing the SA algorithm. The topology of BP neural networks consists of input, hidden, and output layers optimized by the stochastic hill-climbing algorithm.	Suspension bridge	The Runyang Yangzi suspension bridge's hanger damage and its pattern could be successfully identified by the enhanced BP neural networks employing SA.
Bayissa and Haritos [102]	2009	Some difficulties, such as high-dimensionality of search space, nonlinearity, modeling error, and measurement noise, are encountered in the model-based damage detection method formulated as an optimization problem. This study presents a two-step approach to damage localization and quantification. The presented methodology simultaneously applies non-model-based and model-based methods. The first step considers the damage-sensitive response parameters (DSRP) as a non-model-based method. The model-based technique minimizes an objective function via adaptive simulated annealing (ASA). ASA was employed as an optimization algorithm to address the challenge of extensive computation time in the standard SA.	DSRP was initially determined by the statistical moments to find the damaged elements of the structure. In the second step, ASA is adopted using a model-based method to identify the damage severity by minimizing an objective function based on the DSRP.	Simply supported beam I-40 bridge	The results indicate that the presented technique could find the damaged elements using DSRP in the first step. By implementing ASA in the second step, the damage severities can be identified swiftly, even though incomplete and noisy data are utilized.
Begambre and Laier [103]	2009	A new algorithm based on the Nelder–Mead algorithm was developed and known as the particle swarm optimization –simplex algorithm (PSOS) to control the parameters of the PSO. Then, the performance of PSOS was benchmarked with the SA algorithm in different damage detection problems and benchmark functions.	The inverse damage identification problem is formulated as the differences between the measured frequency response function (FRF) and the calculated FRF.	Plane truss Free–Free beam	Combining the standard PSO with the Nelder–Mead algorithm can improve the optimization's capability to find the global optimum in damage detection problems and mathematical benchmark functions. PSOS also performs better than the SA algorithm in all examinations.

Ref.	Year	Objective	Methodology	Structure	Result and Finding
Ferreira and Gomes [104]	2009	A comparative study between the SA algorithm and GA was conducted on the localization and quantification of the damaged elements of the structure only by frequency datasets.	Two objective functions based on natural frequencies are investigated for damage identification. The first objective function is the multiple damage location assurance criterion (MDLAC), and the second is the normalized form of natural frequency differences.	Cantilever beam Simply supported beam	This paper can conclude with the following points: I) Both optimization algorithms, SA and GA, could detect the damages and their corresponding severities with similar accuracy and computation time. II) In most experimental examples, the damaged locations are identified by both GA and SA. However, neither algorithm accurately assessed the damage severity.
Worden et al. [105]	2009	This study compares the SA algorithm and GA for crack detection in beam-like structures.	An objective function has been formed by combining the natural frequency and mode shape components.	A numerical beam model An experimental cantilever beam	The results obtained by numerical and experimental investigations showed that both algorithms (SA and GA) could identify the correct extent and location of the damages. However, the GA needs several runs to provide a reasonable convergence rate.
Marwala [106]	2010	In this study, four optimization algorithms, including GA, PSO, SA, and the response-surface method (RSM), were employed in FEM updating. The efficiency of each algorithm was assessed by the agreement of updated and measured dynamic characteristics. Besides, some results and discussions were outlined on the computing speed.	The differences between computed and measured natural frequencies and related mode shapes were used to create a weighted objective function. Young's modulus of elements in this study was considered as updating parameters.	Free–Free beam Unsymmetrical H-shaped structure	It was observed that PSO could provide more accurate results compared to SA, GA, and RSM. However, RSM is computationally more efficient than other algorithms.
Marwala [107]	2010	Comparing the capability of SA and PSO for FEM updating is the key aim of this research.	The same methodology and objective function, as in Ref. [106], were applied once more in this study.	Free–Free beam Unsymmetrical H-shaped structure	The following results are obtained for the first example, Free–Free beam: I) When using PSO, the error between the measured and updated natural frequencies in the first to fourth modes are 0.0%, 1.8%, 0.0%, and 0.2%, respectively. When using SA, the above errors are 1.9%, 0.2%, 0.5%, and 0.3%. Therefore, the PSO yielded better results with an average error rate of 0.5%. II) When using SA and PSO, the average modal

Ref.	Year	Objective	Methodology	Structure	Result and Finding
					assurance criterion (MAC) value between the measured and updated mode shapes was 0.9989. The following results are obtained for the second example, an unsymmetrical H-shaped structure: I) When using PSO, the error between the measured and updated natural frequencies in the first to fifth modes are 0.0%, 0.4%, 0.1%, 0%, and 1.5%, respectively. When using SA, the above errors are 0.2%, 1.3%, 0.6%, 0.1%, and 2.1%. Hence, the PSO provides accurate results with an average error rate of 0.4%. II) When using PSO and SA, the average MAC values between the measured and updated mode shapes were 0.8434 and 0.8426, respectively. Generally, PSO presented accurate results in terms of FEM updating.
Zhang and Sun [108]	2011	This paper presents a two-step method to localize the damage and quantify its severity. The proposed method relies on BP neural networks in the first stage and a hybrid optimization algorithm known as genetic-simulated annealing (GSA) in the second.	In the first step, a three-layer feedforward neural network is employed to train samples and detect the damaged locations. Then, the damaged elements' extent was identified by minimizing an objective function based on displacement differences.	Suspension bridge	The results from the first step confirm that the BP neural networks can recognize the damage sites in the Nancha bridge. It should be noted that the accuracy of BP neural networks mainly depends on having enough samples coming from finite element analysis or field measurements. In the second step and during the process of estimating the damage severity, the GSA performs a better convergence compared to the GA.
Kourehli et al. [109]	2013	In real-world health monitoring projects, the incompleteness of the measured data is a challenging problem. Consequently, this paper proposes an optimization-based methodology to address the challenge of incomplete static and dynamic measurements.	Three different objective functions with incomplete static and dynamic characteristics are established. The first objective function is the dynamic residue force vector and accepts incomplete mode shapes and frequencies. The second objective	Simply supported beam Plane frame Spring-mass system	The proposed method based on incomplete dynamic and static data and applying the SA algorithm could present promising results for numerical and experimental examples.

Ref.	Year	Objective	Methodology	Structure	Result and Finding
		This study applied the SA algorithm to optimize the objective functions.	function is formulated using the differences between the measured and calculated incomplete displacements. The last objective function is the weighted static residue force vector with incomplete characteristics.		
Al-Wazni et al. [110]	2014	The SA algorithm was employed to minimize a hybrid objective function and determine the location and severity of the structural damages.	A hybrid objective function was proposed, including weighted natural frequency and displacement components. It should be noted that the objective function only contained the first five vibration modes.	Simply supported beam	The presented study illustrates the efficiency of the SA algorithm and the proposed hybrid objective function for accurately detecting the damage in a simply supported beam with ten discretized elements.
Tong et al. [111]	2014	An improved version of the SA algorithm with search capability in multiple dimensions was developed. This modified version attempts to provide an optimal combination of sensor configurations. The performance of the improved SA algorithm was also compared with that of GA. **Note:** The optimal sensor placement is an essential phase in the vibration-based SHM methods.	Three objective functions were considered to solve the optimal sensor placement problem with two hundred sensor location candidates. The fisher information matrix (FIM), the mode shapes' mean square error (MSE), and the MAC as the sensor arrangement criteria are used to establish the first, second, and third objective functions.	Rectangular concrete slab	The results indicate that the proposed method outperforms GA and standard SA regarding optimal sensor placement. Besides, more minor mode shape errors were obtained using MAC and MSE as the objective functions. The results indicate that the MAC function performs better in the optimal arrangement of many sensors.
Stutz et al. [112]	2015	This paper presents a damage identification approach defined as an inverse problem through the minimization of an objective function using four optimization algorithms: differential evolution stochastic optimization (DESO), PSO, SA, and Luus–Jaakola.	The differences between the measured and calculated flexibility matrix defined an objective function. It should be emphasized that the statically reduced stiffness matrix is applied to form the reduced-order flexibility matrix.	Simply supported beam	Results showed that the flexibility matrix is a sensitive index in damage identification, and DESO yielded satisfactory results compared with other optimization techniques, including SA, PSO, and Luus–Jaakola. The proposed method can work under noisy conditions and incomplete measured data.
Astroza et al. [113]	2016	The computational efficiency, accuracy, and convergence rate of the conventional SA method were enhanced by a hybrid technique known as the SA-unscented Kalman filter. This modified	Two objective functions based on acceleration time series data and dynamic characteristics such as natural frequencies and mode shapes are established to solve the optimization	Steel frame building	The introduced SA-unscented Kalman filter can modify the accuracy, computational cost, and convergence rate of the conventional SA. Additionally, using an objective function based on acceleration time series data with six unknown parameters

Ref.	Year	Objective	Methodology	Structure	Result and Finding
		version was employed in FEM updating.	problem. For the first time, only two parameters are considered to be unknown. Then, the FEM updating problem is performed by six unknown parameters.		provides better results in FEM updating.
Alalikhan et al. [114]	2016	In this study, the application of the SA algorithm and Tabu search (TS) algorithm is demonstrated in the FEM calibration and damage detection of an experimental example.	Two weighted objective functions were designed to be minimized by optimization algorithms. In the first objective function, there is a contribution of natural frequencies, MAC values, and mode shapes. However, the second objective function is based on the natural frequencies and mode shapes.	Overhang steel beam	The overall results revealed that both optimization algorithms (SA and TS) are pretty effective in FEM updating and damage identification. However, more investigations on the complex structural models are essential to approve the robustness of the proposed methodology.
Guan et al. [115]	2017	A two-step method is presented, including wavelet analysis and the application of optimization algorithms in vibration-based damage detection problems. The SA and GA are combined to find the global optimal solutions swiftly.	The first step consists of the wavelet analysis to identify the damaged elements. Then, the severity of the damaged elements is estimated by an optimization procedure. For this purpose, the hybrid optimization algorithm (SAGA) is applied to minimize a weighted objective function defined through the sum of the differences between the measured and calculated frequencies and their corresponding mode shapes.	Continuous beam	In addition to accurately localizing the damaged elements, the proposed hybrid technique (SAGA) can also predict the damage's severity.
Kourehli [116]	2017	This study identifies the structural damage parameters by optimizing three kinds of objective functions with dynamic and static properties. The SA is also adopted as an optimization algorithm. Natural frequencies are contaminated with a certain percentage of noise to simulate the real measurement conditions. To study modeling errors, perturbations in elemental stiffness and mass matrices are also implemented.	The dynamic residue force vector, static residue force vector, and the discrepancy between the calculated and measured displacements are practiced as the objective functions. This paper's methodology and objective functions are similar to those presented by Kourehli [109], but this study applies complete measurements instead of incomplete ones.	Plane frame Cantilever plate IASC-ASCE benchmark problem	Another confirmation was made of the effectiveness of the damage identification approach, which is based on the SA algorithm and three objective functions [109] with static and dynamic properties.

Ref.	Year	Objective	Methodology	Structure	Result and Finding
Mišković et al. [117]	2018	After the successful application of SA and TS algorithms for both purposes of FEM updating and damage identification in simple structures [114], the capability of these algorithms was examined by a complex structure.	The experimental modal analysis is carried out for an undamaged and damaged grid bridge. The bridge under the experiment was excited by ambient vibration, while eight accelerometers were placed on it to collect data. Then, ARTeMIS Modal software was used to extract the natural frequencies and mode shapes from the time-series data set. Two different damage scenarios with and without additional mass were considered. In the first scenario, the damage ratio of 0.4 was implemented on element 54. The second damage scenario has an induced damage ratio of 0.4 on element 200. The objective function was optimized utilizing developed routines in MATLAB, while the FEM analyses were performed using the ANSYS software. The only frequency-based objective function was applied to FEM updating. Combining the characteristics of natural frequencies and mode shapes were considered to formulate the weighted objective functions for damage detection.	Steel grid bridge	The results showed that the SA and TS are practical tools for solving vibration-based damage detection problems. The SA and TS could provide a good agreement between the experimental and calibrated models regarding FEM updating. Besides, TS and SA have fast convergence and high accuracy to explore a large search space and detect damaged elements and their extents.
Xiao et al. [118]	2019	This paper applies GA and SA to minimize an objective function relying on strain measurements for damage identification in a large-scale bridge.	An objective function between the calculated strain and measured strain was defined. Changes in the structural elements' cross-sectional area are considered the design variables.	Klehini river bridge	Where GA is used, the objective function value after 51 iterations was 4.81131e-16. The objective function value after 51 iterations was also 9.84959e-10 when using the SA algorithm. It can be concluded that GA provides a better convergence rate compared to those obtained by SA.
Boukellif and Ricoeur [119]	2019	This paper compares GA and SA to solve the inverse problem of crack identification.	Continuous distributions of dislocation densities were used to model the cracks and boundaries.	Infinite and semi-infinite plate	These results came from this paper: I. The arrangement of the strain gauges could not remarkably affect the

Ref.	Year	Objective	Methodology	Structure	Result and Finding
			The presented methodology is also based on the strain measurements achieved from various locations on the surface of the plates.		solution to the inverse problem. II. The results of the inverse problem can be significantly improved by increasing the number of measurement locations. III. SA is not a suitable algorithm for identifying several crack parameters. However, GA can be considered a robust tool for optimizing many variables. To accurately identify the crack parameters such as position, length, and inclination angles, the measurement errors in the strains should not exceed ±5−10%.
Cui and Scalea [120]	2019	This paper investigates the performance of the ultrasonic guided waves and the SA algorithm for the characterization of the elastic properties of laminated composites.	The semi-analytical finite element (SAFE) method was utilized to predict the ultrasonic guided wave propagation in laminated composites. A cost function is formulated based on the discrepancy metric between true and predicted phase velocity curves. To correctly identify laminated composites' elastic properties, the SA algorithm should minimize the objective function. **Note:** For the purpose of damage detection, it would be helpful to determine the elastic properties of laminated composites.	Composite plates	The three frequently used guided modes in SHM fields, including flexural mode (A_0), axial mode (S_0), and shear-horizontal mode (SH_0), are taken into account to identify the properties of laminated composites during an optimization procedure with the assistance of the SA and phase velocity curves as an objective function. This study examined three different types of laminates, including quasi-isotropic, fully anisotropic, and unidirectional. The summary of results can be listed as follows: I. For all types of laminates, laminate axial stiffness (E_x) and longitudinal lamina modulus (E_{11}) are effectively identified by modes A_0 and S_0 propagating along *x*. II. For the anisotropic and quasi-isotropic laminates, E_x and E_{11} are adequately determined by mode SH_0 propagating along *x*. III. The laminate transverse axial stiffness (E_y) and lamina transverse modulus (E_{22}=E_{33}) can be accurately recognized by modes A_0 and S_0 propagating along *x*. IV. The in-plane shear stiffness of the laminate (G_{xy}) and in-plane shear modulus of the lamina

Ref.	Year	Objective	Methodology	Structure	Result and Finding
					(G_{12}=G_{13}) are best identified by mode SH_0. V. The in-plane shear modulus for all types of laminates is appropriately identified by mode A_0 propagating along *x*. VI. For all laminates under consideration, transverse stiffness (E_y), longitudinal stiffness (E_x), transverse flexural rigidity (K_y), and axial rigidity (K_x) can be effectively determined by modes A_0 and S_0 propagating along *x*. VII. The torsional rigidity (K_{xy}) of laminates is recognized by either SH_0, A_0, or S_0. This study suggests experimental verification of numerical studies for future works.
Cui and Scalea [121]	2021	The central objective of this article is the experimental validation of the recently published methodology [120] based on the SA algorithm and ultrasonic guided waves for the nondestructive identification of elastic properties of composite plates.	The SA algorithm minimizes an objective function in phase velocity curves, similar to Cui and Scalea [120]. The SAFE method predicts ultrasonic guided wave propagation in laminated composites.	Composite plates	The experimental study demonstrates that using ultrasonic guided wave data and SA algorithms as an optimizer can be considered a potential tool for the characterization of composite plates.
Hu and Zhang [122]	2021	This paper presents a two-step damage identification approach using the smooth orthogonal decomposition (SOD) method and an improved version of beetle antennae search algorithm (BAS). The fusion strategy of the SA algorithm was applied to BAS to establish a better optimization ability. However, improved BAS has some drawbacks, such as low accuracy and slow convergence for solving optimization problems in large search spaces. Therefore, this study attempts to reduce the search space by excluding undamaged elements in the first step.	In the first step, the damaged members are identified by a damage localization technique called SOD. Finally, the frequency-based objective function was minimized by enhanced BAS to determine the extent of the damaged elements.	Simply supported beam Cantilever beam	The overall results of this paper can be expressed as follows: I. Where improved BAS is applied alone for damage detection in symmetric structures, the damaged elements are identified wrongly. By employing the SOD method at the first step, the challenge of false identification of symmetric structures could be addressed. II. The proposed two-step method can function adequately even for noisy inputs (0.2% and 0.5%). However, the efficiency of this method should be investigated under high noise levels.

Table 2: A review of the application of the SA algorithm in SHM.

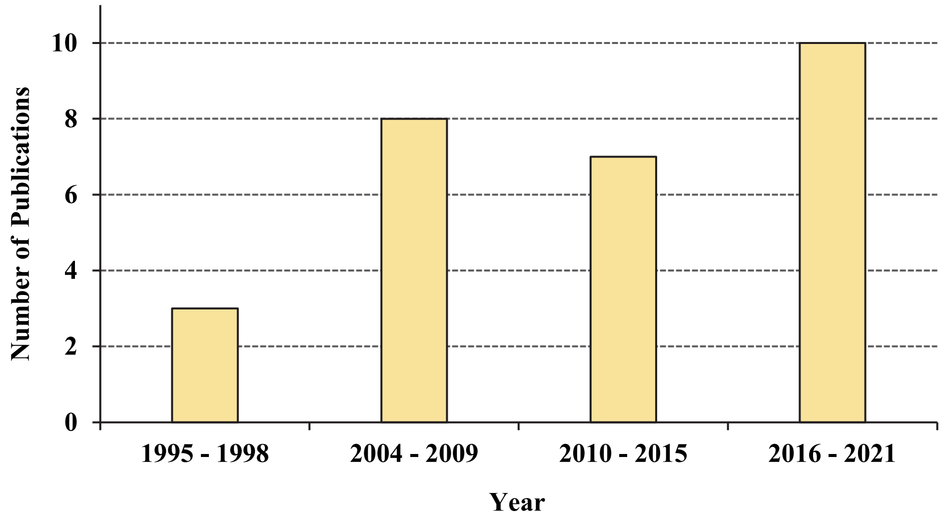


Figure 5: Number of publications in the field of SHM.

Fig. 5 displays the classified number of publications by years. It is clear that optimization-based SHM approaches have advanced significantly in recent years. Fig. 6 shows the contribution of the publications on different parts of SHM, such as FEM updating, crack detection, the combination of FEM updating and damage detection, system identification, and optimal sensor placement. It is obvious that the primary contribution of previously published articles is damage detection.

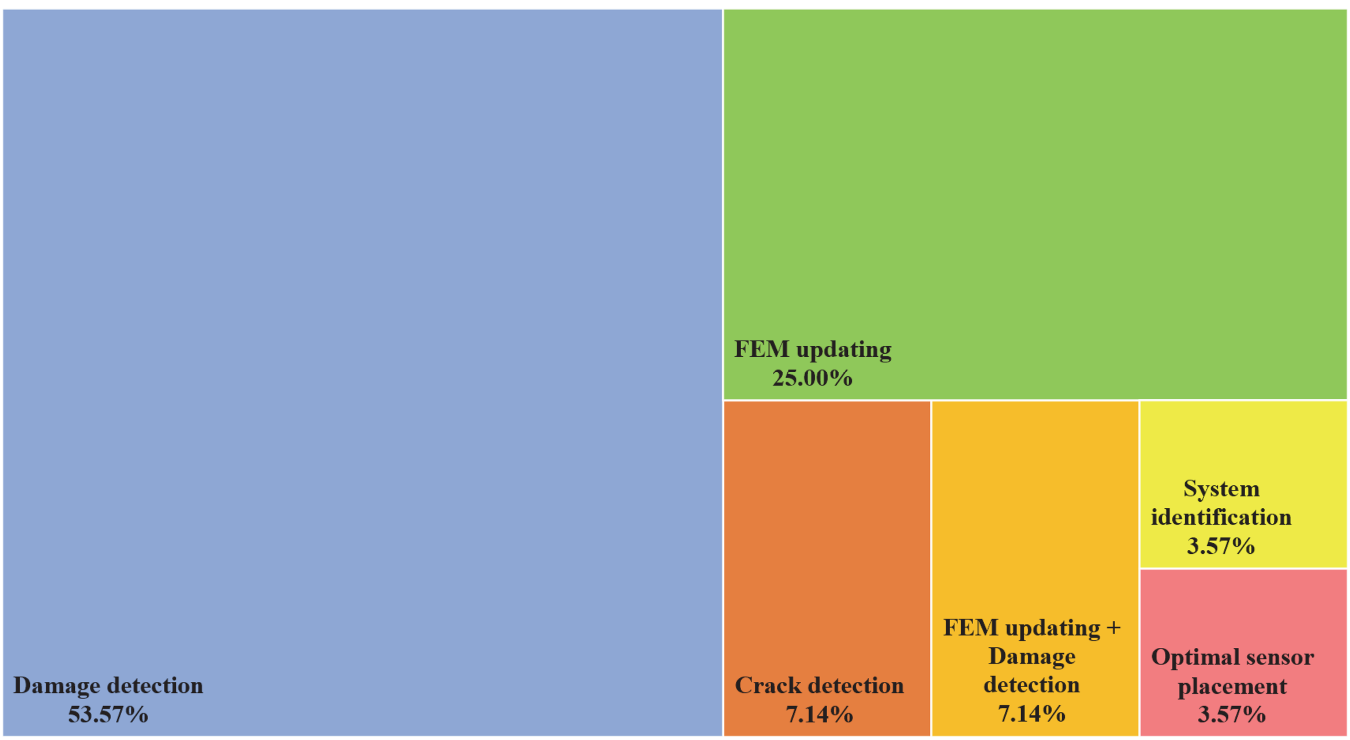


Figure 6: Contribution of the publications in fields of damage detection, FEM updating, crack detection, FEM updating+damage detection, system identification, and optimal sensor placement.

The allocation of employed structures to demonstrate the performance of proposed methodologies is illustrated in Fig. 7. Beam-like structures are the most commonly used example to validate the many approaches in the domain of SHM, as seen in Fig. 7. Fig. 8 depicts the classification of used objective functions based on the number of publications.

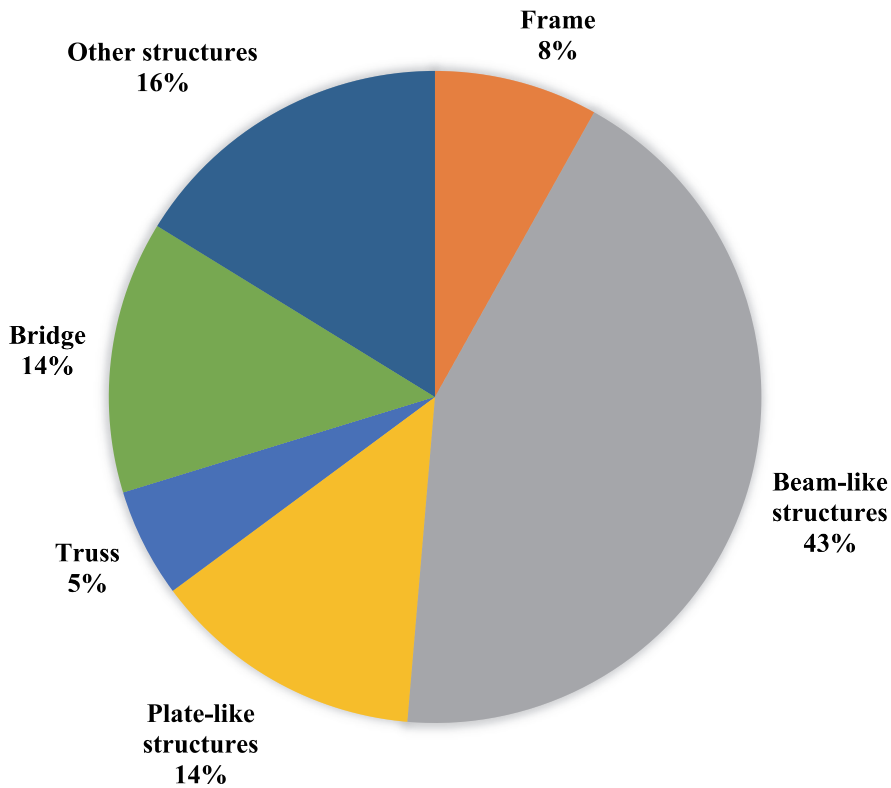


Figure 7: The allocation of employed structures to illustrate the efficiency of presented methodologies in the publications.

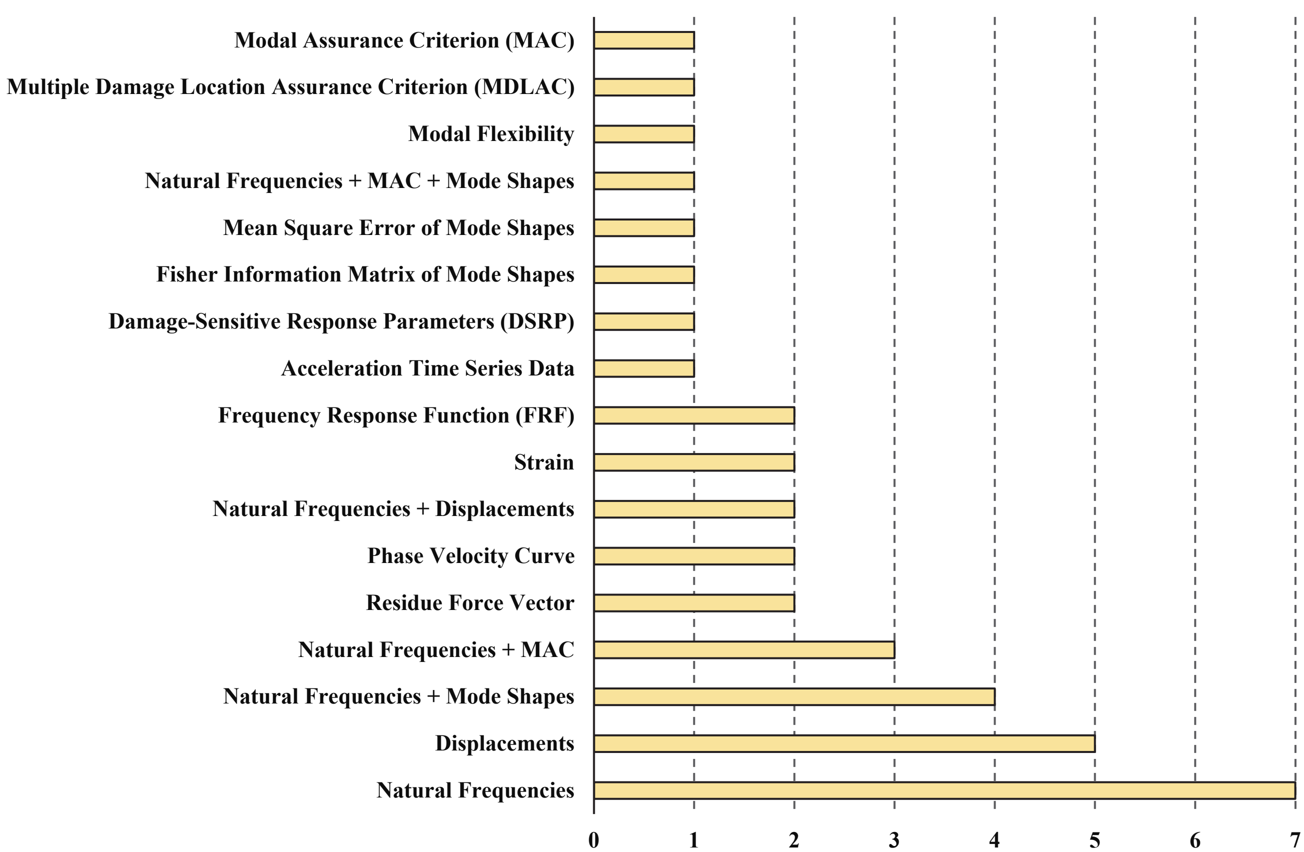


Figure 8: The classification of applied objective functions by the number of publications.

Discussion

Discussion of a subject must include asking and responding to questions. Asking questions and the attempt for solutions is the foundation of science. Questioning helps bring about the true spirit of science and plays a vital role in promoting scientists [123]. Tab. 3 presents several critical questions and their answers to make an efficient discussion on the application of SA in SHM.

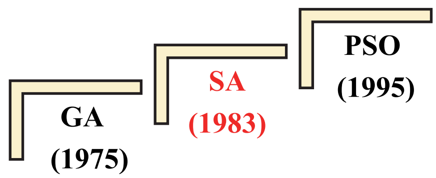
Questions	Answers
0. Is SA the oldest algorithm among other traditional optimization techniques?	No, the SA algorithm is not the oldest [66]. GA was proposed by Holland in 1975 [124]. Then, the SA algorithm was introduced by Kirkpatrick et al. in 1983 [67]. Another popular optimization algorithm, namely PSO, was developed by Kennedy and Eberhart in 1995 [125]. 
1. Why are weighted objective functions applied in several studies [94,99,106,114,115,117]?	The weighted sum method is a simple yet practical technique for solving multi-objective optimization problems. As shown in Eqn. (5), multiple objective functions are combined into a single objective function by multiplying every objective function by a weighting factor [126,127]: $F(x) = w_1 f_1(x) + w_2 f_2(x) + \cdots + w_n f_n(x)$ (5) where w represents the weighting factor.
2. Some studies propose two-step methods [100,102,108,115,122]; what is the necessity of implementing these methodologies?	The proposed two-step methods initially attempt to reduce the dimension of search space by eliminating undamaged elements because optimization algorithms can function accurately in narrowed search space. Besides, the computation cost is dramatically reduced when optimizing a small number of variables.
3. What is the advantage of hybrid algorithms [95,98] based on the SA algorithm and GA?	GA is a powerful global optimization method. However, this algorithm is poor in hill-climbing. Therefore, the weak hill-climbing capacity of GA and the problem of slow convergence could be addressed by the combination of GA and SA.
4. Is there any variant of the SA algorithm to reduce the computation time?	To reduce the computation time in the optimization procedure conducted by the standard SA algorithm, a new variant, namely ASA, was proposed by Bayissa and Haritos [102]. ASA was employed as a part of the damage assessment methodology, and both numerical and experimental examples validated its effectiveness.
5. Is there any inspiration from SA to develop a new algorithm?	As there is a famous proverb, all new ideas are combinations of old ones; it is possible to develop novel algorithms from old ones. In this regard, a new version of BAS has been improved by the fusion procedure of the SA algorithm [122].

Table 3: Several questions and answers to make a discussion on the application of SA in SHM.

Conclusions

Implementing an optimization algorithm to minimize the objective function can be considered a widely used inverse solution for vibration-based damage identification problems. Developing novel optimization techniques has become a fast-growing research field in the recent decade, and the most successful nature-inspired optimizers, such as Grey Wolf, were introduced. However, traditional algorithms such as GA, PSO, and SA have been constantly utilized as global optimizers in damage detection problems.

This paper comprehensively investigated previous studies between 1995 and 2021, and some utilized methodologies were discussed. A summary of around 30 publications in the context of SHM is as follows:

- Most articles were published in the period from 2016 to 2021.
- Beam-like structures make a considerable contribution than other types of structures. In contrast, the lowest contribution is related to truss structures.

- Numerous papers have presented approaches for damage detection (53.57%). The ratio of other methodologies in SHM problems, such as FEM updating, and FEM updating + damage detection, are 25% and 7.14%, respectively. The articles in the field of crack detection (7.14%), system identification (3.57%), and optimal sensor placement (3.57%) are also analyzed.
- Over the past decades, natural frequencies and displacements have been the most utilized characteristics to define the objective function.
- The hybrid algorithms based on GA and SA could address the weakness of GA in hill-climbing and could reduce the computation time of standard GA.
- The weighted sum method was applied to minimize the multi-objective optimization problems by the SA algorithm.
- The damaged elements are initially identified through different methods such as GRA, DSRP, BP neural networks, wavelet analysis, and SOD to improve the accuracy of the SA algorithm for estimating the damage severity in the second step. In the second step, damage severities are predicted by minimizing an objective function based on the SA algorithm.
- Two-step methods were provided as appropriate tools to reduce the computation time for the optimization process by the SA algorithm. Additionally, a new version of the standard SA algorithm called ASA was presented in this regard.

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