Optimization of Piping Supports and Supporting Structure

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Optimization of piping supports is a well-known problem. The paper considers the optimization of piping supports with respect to cost and the loads transmitted to the supporting structural elements, when the orientation of the supporting structure is to be determined. This is the case, when new structural elements need to be added to the existing building structure to support components and piping systems that come as a new addition to a nuclear plant. The analytical target cascading (ATC) method is used for the optimization, combining the support loads from different piping analyses in a hierarchical framework. It is shown that the ATC method can be used for an optimized location of structural elements simultaneously supporting complex piping systems and implemented in a structural analysis software.
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Keywords: piping supports, optimization, ATC, building, cost

1 Introduction

Piping loads are transmitted to the piping supports and subsequently to the building structure. Recent diverse and flexible safety strategy (FLEX) requirements for nuclear plants [1] often necessitate the addition of components and piping systems that need to be supported by new structural elements that are added to the existing building structure.

Optimization of piping supports has been studied by several authors [2–4]. The focus of these studies was the minimization of the supports cost that can be achieved by using fewer and not highly loaded supports. Highly loaded supports transfer to the building structure significant loads that necessitate in many cases the remodeling parts of the building structure or reanalysis of piping systems to achieve compatible structural designs and loading. Previous studies dealt with seismic load and deadweight, using the genetic algorithms (GA) optimization method [3]. Other studies focused on the supports stiffness, where only certain frequencies could excite the piping under vibration or seismic load [5].

In this paper, the use of newly added structural elements, having restraints on carrying loads, is considered in the optimization problem. The supports location is initially optimized with respect to the cost by satisfying all design requirements such as settlement. Figure 1 presents requirements for the proper placement of supports. Loading on piping includes sustained, thermal, seismic, and mechanical loads. Existing optimization analyses focus on piping and supports. The paper introduces the optimization of the location of the newly added structural elements (beams) to the existing building structure with respect to the transmitted loads from different piping systems. Integration of the results of the piping analyses is achieved by using the ATC [6], which is a hierarchical systems optimization method. More specifically, the ATC method uses the individually optimized support loads and location of structural elements and provides a joint solution for the placement of structural elements, which is overall consistent and optimal.

2 Support Cost

In this paper, the capital cost of variable springs, C_s, is defined as a function of the applied force, F_k, as in Ref. [3] and additionally for other type of supports, which are independent of the applied force but rather dependent on the pipe size, the cost C_c is considered constant. Equation (1) shows the optimization function that minimizes the total supports cost, C, in U.S. dollars

$$\min(C) = \min(C_s + C_c) = \min\left(\sum_{k=1}^{n1} aF_k^b + \sum_{m=1}^{n2} C_{cm}\right) \quad (1)$$

where C_{cm} is the capital cost of mth support depending only on pipe size in U.S. dollars, F_k is the applied force on kth support in Newton, $n1$ is the number of supports, whose cost depends on the applied force (i.e., springs), $n2$ is the number of supports with cost depending on pipe size, and a, b are the power best fit curve constants relating applied load/force to capital cost are based on data for springs presented in Ref. [3]. More specifically, the constants a and b attain the values of 1.436 and 0.260, respectively.

From Eq. (1), it can be seen that minimization of cost can be achieved by reducing the numbers of supports n, with $n = n1 + n2$. Additionally, for supports $n1$, reduced cost is achieved by reducing the acting load on variable spring supports.

3 Supporting Structure

In this paper, as supporting structure the building structural elements in direct contact with the piping supports, more specifically beams, are considered. In the ASME B&PV Code, Section III, Div. 1, Subsection NF, the boundaries between the building structure and piping supports are specified, e.g., see Fig. 2. The main catalog items referred to as the primary steel of the support and the support steel that connects to the building, referred to as secondary steel, are considered to transmit securely the loading to the adjacent structural elements (building). The transmitted loading consists of the forces acting on the primary support steel, vertical or horizontal based on the type of restraint on piping, and the

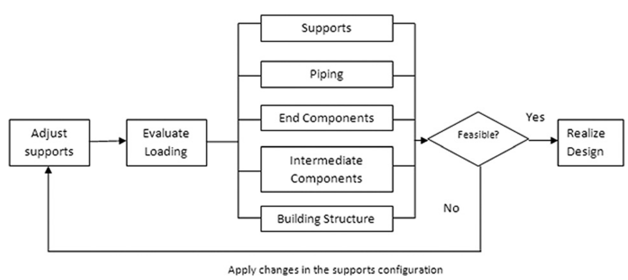

Fig. 1 Supports adjustment relevant to systems components for optimum design

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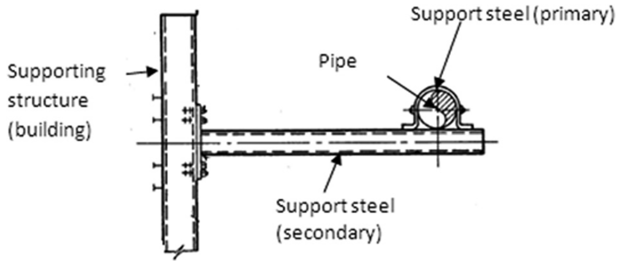

Fig. 2 Boundary between piping support and supporting structure

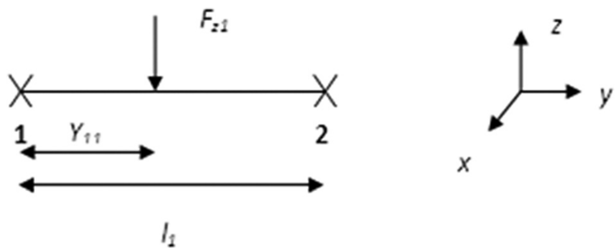

Fig. 3 Structural element $j=1$ fixed at end points $i=1$ and $i=2$

respective moments that these forces create on the structural elements, because they act at a distance from them.

Equations (2)–(7) show the difference of forces and moments exerted on the adjacent supporting structure and respective allowable loads. The allowable loads with subscript u can be an input from the building structural analysis, providing the additional load that can be sustained by the structural elements in addition to any other loading from the building, other equipment, etc. Figure 3 defines the coordinate system used for the structural elements and piping

$$P_{xij} = F_{xij} - F_{xuij} \tag{2}$$

$$P_{yij} = F_{yij} - F_{yuij} \tag{3}$$

$$P_{zij} = F_{zij} - F_{zuij} \tag{4}$$

$$S_{xij} = M_{xij} - M_{xuij} \tag{5}$$

$$S_{yij} = M_{yij} - M_{yuij} \tag{6}$$

$$S_{zij} = M_{zij} - M_{zuij} \tag{7}$$

where F_{xij} is the force (N) in x direction due to piping load at side i of fixed element j of adjacent supporting structure, F_{yij} is the force (N) in y direction due to piping load at side i of fixed element j of adjacent supporting structure, F_{zij} is the force (N) in z direction due to piping load at side i of fixed element j of adjacent supporting structure, M_{xij} is the bending moment (N·m) in x direction due to piping load at side i of element j of adjacent supporting structure, M_{yij} is the torsion moment (N·m) in y direction due to piping load at side i of fixed element j of adjacent supporting structure, M_{zij} is the bending moment (N·m) in z direction due to piping load at side i of fixed element j of adjacent supporting structure, F_{xuij} is the allowable force (N) in x direction due to piping load at side i of fixed element j of adjacent supporting structure, F_{yuij} is the allowable force (N) in y direction due to piping load at side i of fixed element j of adjacent supporting structure, F_{zuij} is the allowable force (N) in z-axis due to piping load at side i of fixed element j of adjacent supporting structure, M_{xuij} is the allowable bending moment (N·m) in x direction due to piping load at side i of fixed element j of adjacent supporting structure, M_{yuij} is the allowable torsion moment (N·m) in y direction due to piping load at side i of fixed element j of adjacent supporting structure, M_{zuij} is the allowable bending moment (N·m) in z direction due to piping load at side i of fixed element j of adjacent supporting structure, $i=1, 2$ and $j=1, 2,\ldots, p$, and p is the number of beams.

By considering Eqs. (2)–(7) in addition to Eq. (1), it is apparent that the formulated problem is multi-objective. There are several approaches to handle multi-objective optimization problems [7,8]. In this case, by considering fixed-end structural elements, i.e., beams, where three forces and three moments may be developed at each fixed end, and by considering also Eq. (1), the maximum number of the minimization objective functions is $12p+1$, where p is the number of beams involved. The number of the objective functions can be significantly reduced for other boundary conditions and when only the maximum force and moment at each node of the structural element are considered. To reduce the number of objective functions, the $(12{*}p)$ objective functions for the structural elements can be combined to a single optimization function, as Eq. (8) shows. Similar techniques are suggested by Koski and Silvennoinen [9], where the objective functions are reduced to one with different weight factors. The objective functions in this case are considered equally important, having weight factors equal to one

$$\min(A) = \min\left(\sum_{i=1,j=1}^{2,p} (P_{xij} + P_{yij} + P_{zij} + S_{xij} + S_{yij} + S_{zij})\right) \tag{8}$$

subject to
$\max(P_{xij}, P_{yij}, P_{zij}, S_{xij}, S_{yij}, S_{zij}) \le 0$
$0.1 \le y_{kj} \le l_j$

and y_{kj} and l_j are shown in Fig. 3 for element $j=1$. These constraints are necessary to ensure that the proposed locations of supports meet geometrical and allowable loads constraints.

4 Optimization Problem

The multi-objective optimization problem is reduced to a bi-objective problem, defined by Eqs. (1) and (8). All relevant ASME code [10] equations and functionality requirements are ensured for piping. As an example, the constraint functions g_1–g_3 show a few code requirements [10] and g_4–g_7 functionality requirements

$$g_1 = B_1\frac{PD_o}{2t_n} + B_2\frac{M_A}{Z} - 1.5S_h \le 0 \tag{9}$$

$$g_2 = \frac{PD_o}{4t_n} + 0.75i\left(\frac{M_A}{Z}\right) + i\left(\frac{M_C}{Z}\right) - (S_h + S_A) \le 0 \tag{10}$$

$$g_3 = B_1\frac{P_D D_o}{2t_n} + B_2'\frac{D_o}{2I}M_E - 3S_m \le 0 \tag{11}$$

$$g_4 = d_{\mathrm{dw}} - d_{\max} \le 0 \tag{12}$$

$$g_5 = F_i - S_{i\mathrm{allow}} \le 0 \tag{13}$$

$$g_6 = M_i - M_{i\mathrm{allow}} \le 0 \tag{14}$$

$$g_7 = G - G_{\mathrm{allow}} \le 0 \tag{15}$$

where B_1, B_2, B_2', i are the stress indices from Table NC-3673.2(b)-1 of Ref. [10], D_o is the pipe outside diameter (mm), F_i is the force transmitted to attached component, with $i=$ square root of sum of squares (SRSS) of shear forces or axial force (N), G is the acceleration developed to valves due to dynamic loads (e.g., earthquake) (m/sec^2), G_{allow} is the allowable acceleration at

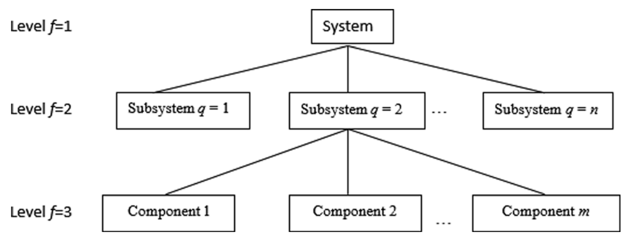

Fig. 4 ATC decomposition in subsystems and components

intermediate components such as valves (m/sec^2), I is the moment of inertia (mm^4), M_A is the resultant moment due to weight and other sustained loads (N mm), M_C is the resultant moment due to thermal expansion loads (N mm), M_E is the amplitude of the resultant moment due to earthquake loading and weight (N mm), M_i is the moment transmitted to the attached components, with i = square root of sum of squares (SRSS) of bending moments or torsion (N mm), $M_{i\text{allow}}$ is the permissible i moment on a component per the manufacturer's requirements (N mm), P is the design pressure (MPa), P_D is the pressure coincident with earthquake (MPa), S_h, S_A, S_m are the allowable stresses as defined in ASME B&PV Code, Section II, Material Properties, 2007 (MPa), $S_{i\text{allow}}$ is the permissible i force on a component per the manufacturer's requirements (N), Z is the section modulus of pipe (mm^3), d_{dw} is the piping deflection due to deadweight, $d_{\max}$ is the permissible deflection due to deadweight, t_n is the pipe nominal thickness (mm).

Equations such as (9)–(11) are checked by the piping analysis program [11]. Equation (12) refers to displacements due to deadweight and assures appropriate distance between supports per criteria in Ref. [12]. Constraints imposed by Eqs. (13) and (14) are addressed usually by the manufacturer of the components to which the piping is attached (e.g., pumps, boilers, etc.). Equation (15) refers to accelerations developed in valves. In addition to the behavioural equations stated above, geometrical properties, particular to each problem, may be part of the optimization, e.g., there can be areas, where the construction of supports is not feasible or overly expensive, etc.

5 Analytical Target Cascading for Optimization

The ATC is a model-based, multilevel, hierarchical optimization method, used for large-scale, complex design systems with a large number of coupled variables. The original problem, as shown in Fig. 4, can be decomposed in multiple levels f and subsystems q. The formulated subsystems create subproblems that share variables with the higher order optimization system/problem along with consistency constraints. The consistency constraints are relaxed, using penalty functions. The subproblems solve the relaxed problem independently until the desired consistency is achieved for the original problem [13]. The ATC method has found applications among others in the automotive [6], aircraft [14], and building industries [15] and several variations of the method have been developed [16].

Optimization of Eqs. (1) and (8) is performed using the ATC method and each subsystem in this case is a piping system with its supports. The optimized beam coordinates from each separate piping analysis are relaxed using penalty functions. The penalty functions consider equally all the subsystems and in this case are the average of the optimized beam coordinates from the different piping analyses. The procedure is iterative. Piping analyses can be performed by different analysis teams and the results are hierarchically integrated in one optimal and consistent solution.

The structural beams receive loads from different piping systems and are allowed under certain restrictions to change their direction in space in order to minimize their sustained loads.

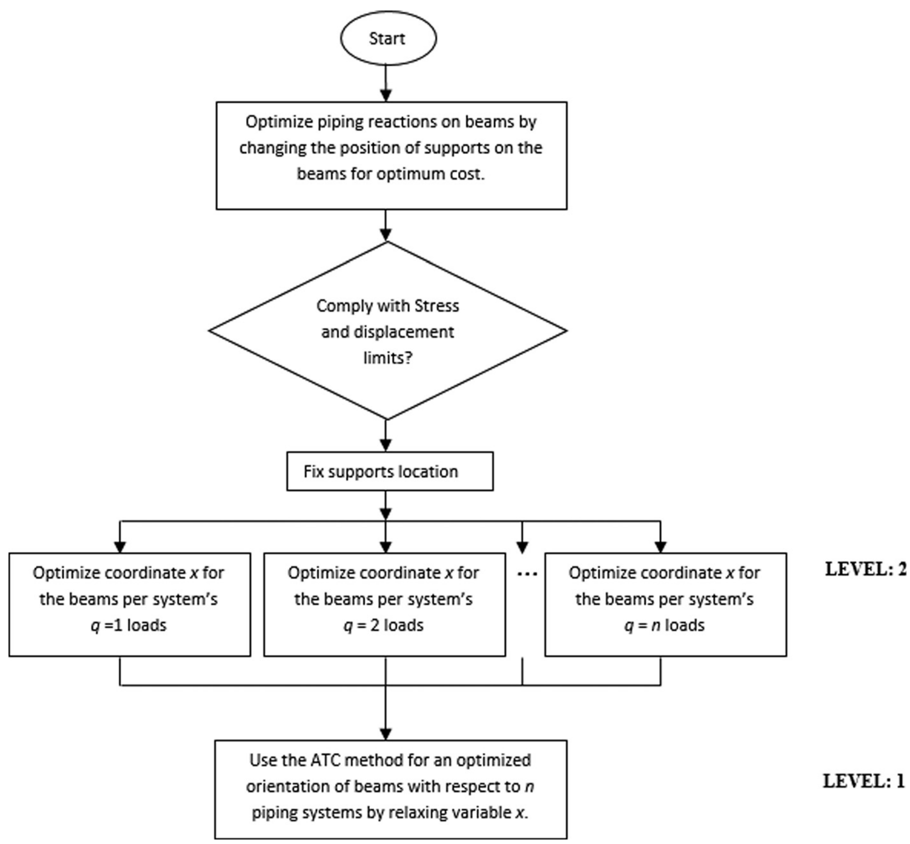

Fig. 5 Flowchart for optimization

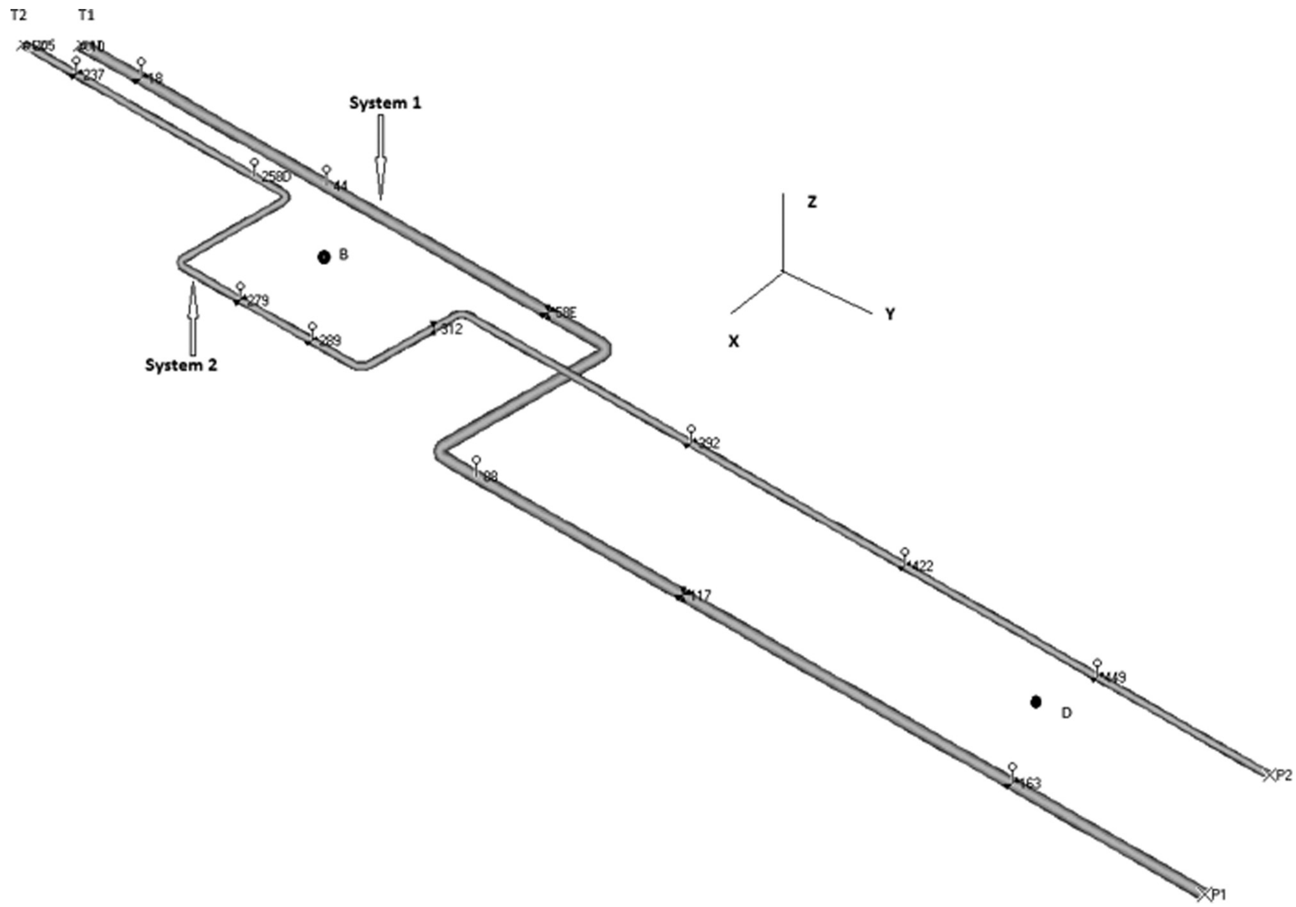

Fig. 6 Piping isometric view with optimized supports, showing physical points B and D from which the four beams need to pass

Minimization of the transmitted piping loading contributes to the overall reduction of loading of the building structure. In this context, a case study is examined that can be expanded to multiple piping systems and structural elements.

6 Case Study

The case study seeks for the optimum location of new structural elements (four beams in close proximity to piping and supports) that should sustain loads from two piping systems by first minimizing the cost of piping supports. The optimization functions of Eqs. (1) and (8) are used. Additional constraints to those presented in Eqs. (9)–(12) are geometrical constraints on the position and number of structural elements. The flowchart in Fig. 5 demonstrates the analysis steps. The main variable of the optimization is the beam coordinate, x, as defined in Fig. 3.

The two piping systems are shown in Fig. 6. They are made of austenitic stainless steel, Type 304, with piping system 1 being NPS8, Sch. 40 (outside diameter 168.28 mm and thickness 7.112 mm) and system 2 NPS6, Sch. 40 (outside diameter 114.30 mm and thickness 6.02 mm). The minimum horizontal distance is 1 m between points T1 and T2 in Fig. 6 and the maximum 4.3 m toward the other end of the piping systems. Piping system 2 is 0.5 m higher than system 1. The design conditions for piping system 1 are 120 °C temperature and 1.1 MPa pressure and for piping system 2 these are, respectively, 150 °C and 1.2 MPa. The piping is seismically excited in three directions with arbitrary response spectra.

Special constraints are applicable for the structural elements that are to transmit the piping loads to the main building structure. More specifically, four new beams (AB, BC, CD, and DE) with an approximate length of 6.10 m can be built at elevation 1.8 m higher than the piping system 1. The exact length of the beams is to be defined as the horizontal coordinate x for points A, C, and E is allowed to change. All axial beam coordinates, y, remain constant and are predefined. Additionally, the beams need to pass through physical points B and D with coordinates: B (1.25, 6.05) and D (2, 18.05). Allowable loads at the fixed end of beams are provided in Table 1. Such constraints are usual, when considering adding new elements in an existing structure. The piping analysis was done with the PIPESTRESS software [11].

The supports are optimized by considering each of the piping systems and beam parameters separately (two subsystems) and checking for each one the compliance with all constraints. The yielded support loads and types of supports get fixed and the capital cost is evaluated as $42,719 for piping system 1 and $70,440 for piping system 2. The top hierarchical system represents the beams ($f = 1$) and the piping systems 1 and 2 are subsystems in a lower level ($f = 2$), according to the schematic provided in Fig. 4.

Table 1 Allowable forces and moments at each end of the beams fixed ends

	Force (kN)	Moment (kN m)
Overall capacity	$Fx = 11.5$ $Fz = 9.5$	$Mx = 10$ $Mz = 22$
Piping system 1	$Fx = 5$ $Fz = 4.5$	$Mx = 4$ $Mz = 9$
Piping system 2	$Fx = 6.5$ $Fz = 5$	$Mx = 6$ $Mz = 13$

Optimization of the beams, namely, of coordinates x_A, x_C, and x_E, can be achieved by minimizing the transferred support loading on beams using Eqs. (16) and (17) for piping systems 1 and 2, respectively.

The objective function for piping system 1 is given as below

$$\min\left\{ \sum_{i=1,j=1}^{2,\rho} (P_{xij} + P_{yij} + P_{zij} + S_{xij} + S_{yij} + S_{zij}) + h * [\mathrm{ABS}(x_{AT} - x_{A1}) + \mathrm{ABS}(x_{CT} - x_{C1}) + \mathrm{ABS}(x_{ET} - x_{E1})] \right\} \tag{16}$$

The objective function for piping system 2 is given as below

$$\min\left\{ \sum_{i=1,j=1}^{2,\rho} (P_{xij} + P_{yij} + P_{zij} + S_{xij} + S_{yij} + S_{zij}) + h * [\mathrm{ABS}(x_{AT} - x_{A2}) + \mathrm{ABS}(x_{CT} - x_{C2}) + \mathrm{ABS}(x_{ET} - x_{E2})] \right\} \tag{17}$$

where

$$x_{AT} = \frac{x_{A1} + x_{A2}}{2}, \quad x_{CT} = \frac{x_{C1} + x_{C2}}{2}, \quad \text{and} \quad x_{ET} = \frac{x_{E1} + x_{E2}}{2} \tag{18}$$

Equations (16) and (17) are derived for each piping system separately by using Eq. (8) and adding the second term with the penalty functions. At each iteration, the target coordinates of points A, C, and E, namely, x_{AT}, x_{CT}, and x_{ET}, are updated with respect to both piping systems and the response values from system 1, x_{A1}, x_{C1}, x_{E1}, and system 2, x_{A2}, x_{C2}, and x_{E2} are penalized, using the target coordinates of Eqs. (18), as convergence for both systems is sought.

The first term of Eqs. (16) and (17) is negative. The penalty function is positive and gets minimized leading to convergence. The constant h, in this case having a value of 100,000, multiplies the penalty functions and aims to make the two terms in objective functions (16) and (17) of the same magnitude. The optimization problem is not smooth and nonlinear. By using different iteration start points for variables x_{A1}, x_{C1}, x_{E1}, x_{A2}, xc_2, and x_{E2} and the generalized reduced gradient method, the existence of local minima was identified. For that reason, the Evolutionary method in Excel, based on genetic algorithms, was used for the minimization of the objective function of each system. Iterations terminated when accuracy of 0.0001 m was achieved for the x coordinates of points A, C, and E.

Table 2 shows separately the results from the optimization of piping system 1 loads and piping system 2 loads, as well as the

Table 2 Beam coordinates based on the ATC decomposition

Structural element	Coordinate	Beginning (m)	End (m)	Optimization result Eq. (8)
Solution based on piping system 1				
Beam 1 (A–B)	x	**0.3757**	1.25	−34,189
	y	0	6.05	
Beam 2 (B–C)	x	1.25	**2.1154**	
	y	6.05	12.05	
Beam 3 (C–D)	x	**2.1154**	2.00	
	y	12.05	18.05	
Beam 4 (D–E)	x	2	**1.7886**	
	y	18.05	24.00	
Solution based on piping system 2				Eq. (8)
Beam 1 (A–B)	x	**0.0034**	1.25	−68,799
	y	0	6.05	
Beam 2 (B–C)	x	1.25	**1.2132**	
	y	6.05	12.05	
Beam 3 (C–D)	x	**1.2132**	2.00	
	y	12.05	18.05	
Beam 4 (D–E)	x	2.00	**2.0600**	
	y	18.05	24.00	
Converged joint solution using ATC				Eqs. (16) and (17)
Beam 1 (A–B)	x	**0.2360**	1.25	System 1: −32,886
	y	0	6.05	
Beam 2 (B–C)	x	1.25	**1.7667**	
	y	6.05	12.05	
Beam 3 (C–D)	x	**1.7667**	2.00	System 2: −68,537
	y	12.05	18.05	
Beam 4 (D–E)	x	2.00	**1.9140**	
	y	18.05	24.00	

Optimization results are shown in boldface.

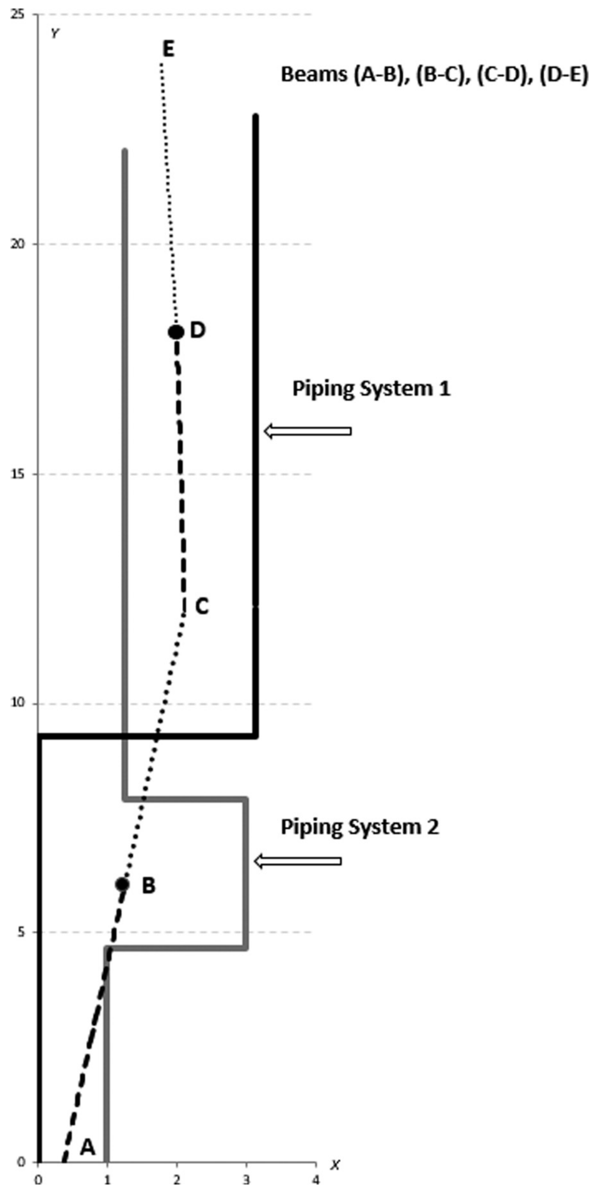

Fig. 7 Layout (X–Y) of beams based only on piping system 1 analysis

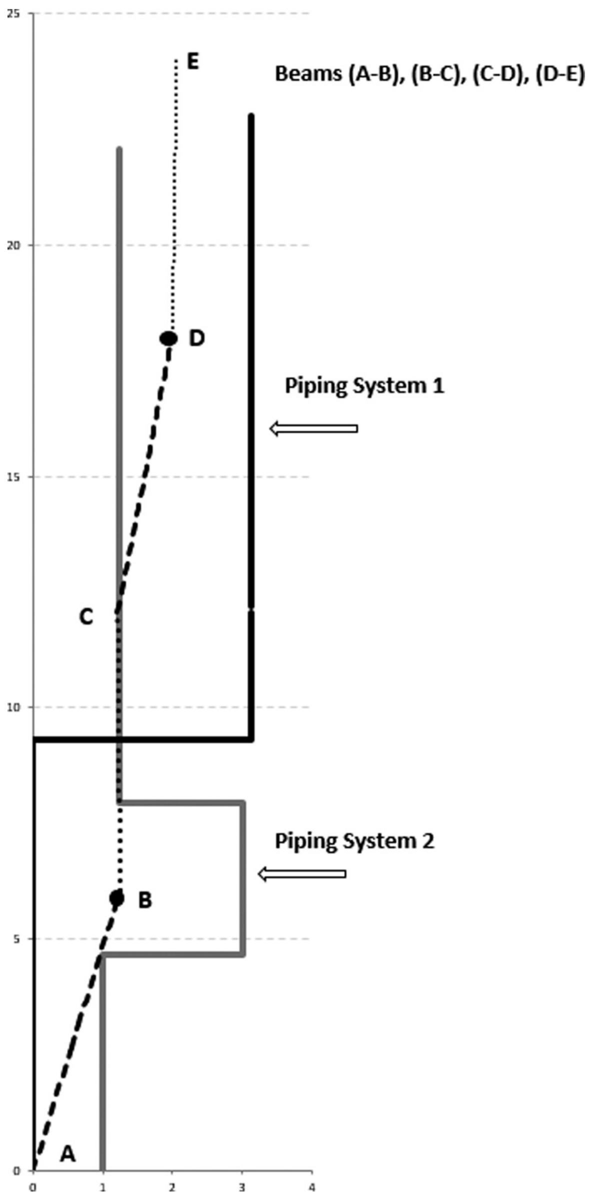

Fig. 8 Layout (*X*–*Y*) of beams based only on piping system 2 analysis

converged results. These results can be graphically seen in Figs. 7 and 8 for piping system 1 and system 2 optimizations, respectively. Figure 9 gives the converged optimal solution, using the principles of the ATC method, for the simultaneous optimization of the beams position with respect to both piping system support loadings. The joint optimal solution is shown between the solutions yielded separately from piping system 1 and 2 optimizations. When comparing the separate solutions with the optimal converged solution in Table 2, piping system 2 solution, with higher loads, is more affected than that of piping system 1.

7 Conclusions

The paper presented the optimization of piping supports that yields minimum loads to be sustained by the adjacent structural elements and minimized the cost for piping supports. Although the examined case only addressed two piping systems, usually the amount of piping involved is very large, making the analysis very complex and the analytical target cascading method a suitable method for the optimization of such problems, because it allows separate analysis results to be combined and provides an overall optimal solution. Additionally, the procedure is possible to be

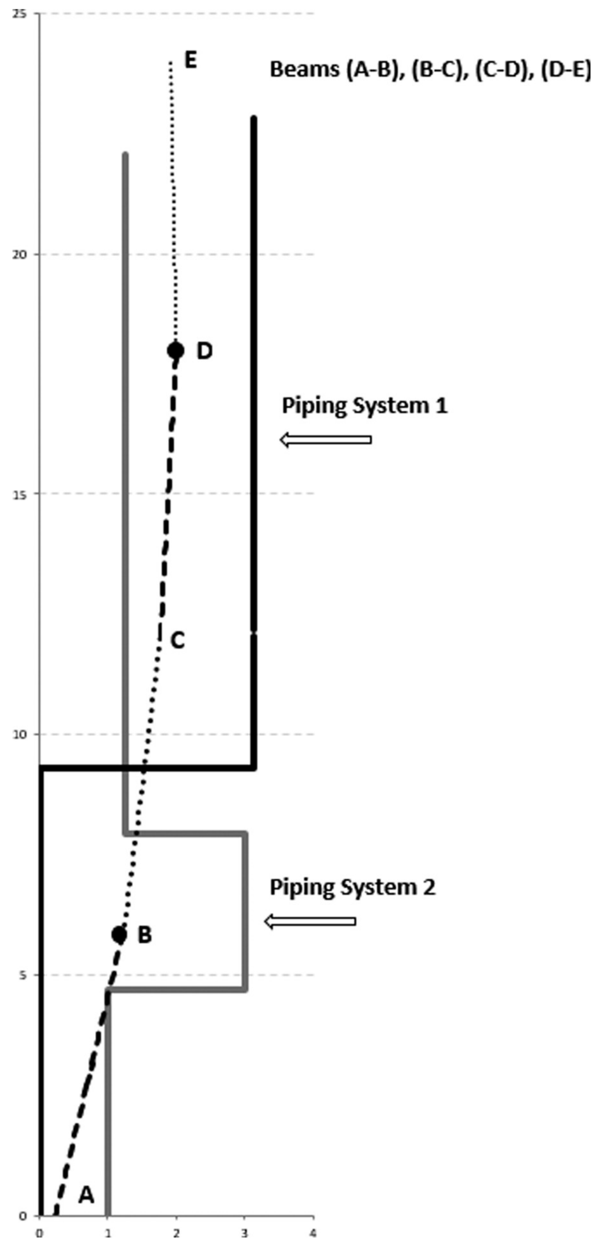

Fig. 9 Layout (*X*–*Y*) of beams based on the converged optimal solution using ATC

integrated in existing structural analysis programs that will allow the change of orientation of new structural elements for the transmitted from the piping loading to be minimized.

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