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Sensitivity-based mathematical optimization models for sustainable infrastructure planning under resource constraints

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Abstract:

Sustainable infrastructure planning over the long haul — including eco-friendly electricity grids, water-resource systems, and green transport routes — takes place within the framework of stringent budgetary, material, and ecological constraints that are often unknown during the planning process. Unlike what is typically regarded as a problem of design optimization, infrastructure planning should be viewed more as a problem of parametrization, whereby optimal solutions shift as parameters of resource perturbation change, and vulnerability is indicated by the magnitude of shift. Conventional sensitivity analysis of nonlinear programming makes use of parametric optimization algorithms, with design and allocation variables responding to the elements of perturbation vector pertaining to environmental condition. In order to guard against multi-source uncertainty and parametric instability, a robust minimax methodology has been developed. Moreover, the generalized Karush-Kuhn-Tucker conditions have been derived using the generalized Mangasarian-Fromovitz qualification, thereby demonstrating the non-empty, convex, bounded structure of the set of multipliers failing to work under conventional Linear Independence Constraint Qualification conditions for non-unique projects. It has been shown that the mapping of the set of constraints is metric subregular, thus ensuring controlled local error bounds close to active boundaries of constraints. Moreover, by imposing strict second-order efficiency requirements on critical cones, the design solutions become locally unique and stable. The results of numerical tests performed on a model network dealing with multiple resources in conditions of interrelated stress, capacity, and ecological impact constraints indicate that both sustainability of the multiplier behavior and performance limit preservation are proven for the given approach.

Keywords: Parametric sensitivity analysis, sustainable infrastructure planning, minimax robustness, generalized mangasarian–fromovitz qualification, metric subregularity, generalized KKT conditions, resource-constrained optimization.

1. Introduction

Long-term planning of sustainable infrastructure such as green energy grids, water-resource networks, and eco-transport corridors is hampered by a conflict between budget price ceilings, availability of materials, and environmental impact limitations, which needs to be taken into consideration over a multi-decade planning period of time. An analysis of logistics distribution centers in terms of economic efficiency and sustainability demonstrates that site selection of resource-limited infrastructure is sensitive to the changes of regional economic and environmental parameters [1]. An inventive energy-aware dynamic scheduling algorithm used for optimizing processes under budget limitations is demonstrated in a similar situation in terms of resource limitation, since scheduling is contingent on the value of changing budgetary parameters and not on a fixed level [2]. Design of best practices for low-impact development of urban runoff management based on global sensitivity analysis in a low-uncertainty situation provides a good example of infrastructure design where GIS and green stormwater infrastructure are indeed sensitive to rainfall and land-use parameters [3]. Research on the role of digital transformation for supply-chain management shows that adjacent logistics systems are sensitive to technological variables that must be included into resource-constrained planning [4].

Infrastructure planning is correctly conceptualized not in terms of an optimization problem but in terms of the sensitivity of system vulnerability to changes in optimal design per resource disturbance. The case of multi objective optimization for low-impact urban stormwater development with additional equity requirements shows that Pareto optimal infrastructure configuration is extremely sensitive to the choice of the equity-cost objectives weighting and highlights the necessity of performing explicit sensitivity analysis as compared to running only a single nominal solution [5]. The case of selecting the optimal project portfolio with the help of the modified version of the Markowitz model proves that in the setting similar to infrastructure project's financial portfolio, the portfolio resilience to parameter disturbances becomes the primary design goal instead of an afterthought [6]. Finally, the development of a robust multio bjective optimization approach for nature-based secondary resource recovery under climate uncertainty proves that infrastructure resource recovery systems optimized for one climate threat scenario appear to deteriorate significantly when assessed in the light of other climate parameters settings motivating the minimax resilience approach proposed in Section 3 [7]. An optimization-driven lightweight block cipher framework was developed to improve cryptographic efficiency, reduce computational complexity, and provide secure data protection for resource-constrained communication systems [18]. An enhanced bee colony algorithm was proposed to solve the traveling salesperson problem by improving the optimization search process, convergence capability, and solution accuracy through swarm intelligence-based strategies [11].

Holistic enhancement of hosting capacity through the deployment of flexibility according to sensitivity analysis and optimizing under uncertainty in contemporary distribution systems shows that the sensitivity coefficients calculated at the nominal operating point can be directly used in the optimization procedure to perform capacity expansion, which is generalized in the present treatment to the entire sustainable infrastructure area [8]. Mathematical modeling of resilient and sustainable renewable-energy integration with hybrid storage technologies within emission constraints and extreme-environmental conditions demonstrates that the concept of infrastructure sustainability in the presence of perturbations requires a direct approach to the governing equations in cases of degenerate constraint configurations appearing near the capacity limits, which is the subject of investigation in Chapter 2.3 [9]. Sensitivity-related adaptive method of rehabilitation of sewer systems is a confirmation of the fact that rehabilitation directions derived from sensitivity analyses remain unchanged in cases of moderate perturbations but change in the degenerate capacity-constraining area indicating the existence of this phenomenon in reality [10]. The application of sensitivity-based maintenance procedures in the area of urban security has provided yet another real application of sensitivity analysis within the stochastic Petri nets theory [11]. Despite the above-mentioned applications of sensitivity analyses, the connection between the classical nonlinear programming sensitivity theory and sustainable infrastructure resource restrictions with complete qualification of constraints and error boundaries has not yet been established. There are three contributions to the relevant body of knowledge. First, the theory of classical nonlinear programming sensitivity is connected with the sustainable infrastructure resource restrictions through the parametric optimization model. Second, the approach to the treatment of multi-source uncertainty through minimax optimization is proposed. Third, the existence of the second-order sufficiency condition and the corresponding error boundaries in the degenerate area of constraints has been verified.

2. Sustainable infrastructure optimization model and geometric preliminaries

2.1. Sustainable infrastructure optimization model

The general constrained parametric optimization problem is formulated as

$$\min_{x\in\mathbb{R}^n} f(x,\theta) \quad \text{subject to} \quad g_i(x,\theta)\le 0,\ i=1,\dots,m;\ h_j(x,\theta)=0,\ j=1,\dots,p \tag{1}$$

Assume that x denotes a vector of collected infrastructure design and resource allocation elements (like capacity investment, material allocation, and transport corridor routes), $\theta \in \Theta \subset \mathbb{R}^q$ denotes an environmental perturbation or resource disturbance parameter vector (like rainfall intensity, budget limit, material price, and emissions limit), and g_i, h_j denote the constraints in terms of resources, capacity, and environmental impact jointly parameterized in (x,θ). The optimal power flow-based arrangement allows for the coordinated active and reactive power control to overcome voltage violations in the distribution networks rich in smart inverters and creates the first direct set of equivalents of Equation (1) with the θ indicating a variable of renewable generation and demand parameters. Moreover, the AI-based decarbonization supply chain strategies for sustainable carbon removal can be referred to as the second respective cases of equation (1), where the parameter of disturbance θ is an indicator for changing carbon pricing or restrictive regulations.

2.2. Tangent cones and first-order data

At a feasible design x^* under a fixed perturbation θ, the Bouligand (contingent) tangent cone is

$$T_\Omega(x^*,\theta)=\{d\in\mathbb{R}^n:\exists t_n\downarrow 0,\ d_n\to d \text{ with } x^*+t_n d_n \text{ feasible under } \theta\} \tag{2}$$

and the linearized feasible cone is

$$L(x^*,\theta)=\left\{d\in\mathbb{R}^n:\nabla_x g_i(x^*,\theta)^T d\le 0,\ i\in I(x^*,\theta);\ \nabla_x h_j(x^*,\theta)^T d=0,\ j=1,\dots,p\right\} \tag{3}$$

Where $I(x^*,\theta)$ reflects the constraints in resources and capacities under the perturbation caused by the parameter θ, the generalized Mangasarian-Fromovitz constraint qualifications (MFCQs) have been applied for $T_\Omega(x^*,\theta)=L(x^*,\theta)$ consistently in an area near the nominal value of a parameter, which meets the demands of the fuzzy optimization which correspondingly evaluates and analyses supply chain configurations in dairy production and sustainable design approaches. In another example of applying the geometric correctness guaranteed by Eq. (2)-(3), allude to a scenario-learning-decision framework which has been made possible with the use of large language models suitable for effective emergency management where it would be necessary to quickly change plans while dealing with an ongoing emergency incident.

2.3 Metric Subregularity and Error Bounds

The constraint mapping is defined as $G(x,\theta)=\left(g_1(x,\theta),\dots,g_m(x,\theta),h_1(x,\theta),\dots,h_p(x,\theta)\right)$, and G is said to be metrically subregular at (x^*,θ^*) relative to the set $\mathcal{K}=\mathbb{R}_-^m\times\{0\}^p$ if there exists $\kappa>0$ and a neighborhood U of (x^*,θ^*) such that

$$\operatorname{dist}\left(x, G(\cdot,\theta)^{-1}(\mathcal{K})\right)\le \kappa\cdot\operatorname{dist}(G(x,\theta),\mathcal{K}) \quad \text{for all } (x,\theta)\in U \tag{4}$$

The text is focused on error bounds in relation to the constraints present in the process where the parameter θ tends to a degenerate set. The client selection algorithms used in federated learning for devices with limited resources are analyzed using game theory techniques, thereby creating another example of a resource-limited space where a similar type of condition of stability is employed – controlled selection is possible for certain parameters of the devices which are close to limits. Moreover, the importance of environmental sensitivity analysis for SEA in sustainable tourism planning is reviewed in the paper, thus unveiling the regular occurrence of unmanaged degeneration of environments for planning purposes that Eq. (4) seeks to eliminate.

3. Sensitivity analysis and minimax duality framework

3.1. Lagrangian saddle-point structure

The parametric sensitivity model of equation (1) is transformed into an augmented minimax optimization problem

over the Lagrange multipliers $\mu \geq 0$ and ν, given by

$$\mathcal{L}(x, \mu, \nu; \theta) = f(x, \theta) + \sum_{i=1}^{m} \mu_i \, g_i(x, \theta) + \sum_{j=1}^{p} \nu_j \, h_j(x, \theta) \tag{5}$$

With the parametric optimal value function defined as

$$V(\theta) = \min_{x} \max_{\mu \geq 0, \nu} \mathcal{L}(x, \mu, \nu; \theta) \tag{6}$$

How sensitive it is to θ by the values of the multipliers attained at the appropriate saddle point, following the classical envelope theorem generalized to cases of nonsmoothness and constraints degeneracy described in Section 2.3. Sustainability indicators can be incorporated into the design course of footbridges in the frame of decision support system that includes environmental, economic, and structural performance and represents a structural - infrastructure example of the saddle point character of eq. (5)-(6).

3.2. Generalized KKT conditions and multiplier behavior

Generalized Karush–Kuhn–Tucker (G-KKT) conditions for the parametric problem of equation (1) are derived as

$$0 = \nabla_x f(x^*, \theta) + \sum_{i} \mu_i^* \, \nabla_x g_i(x^*, \theta) + \sum_{j} \nu_j^* \, \nabla_x h_j(x^*, \theta), \quad \mu_i^* \geq 0, \quad \mu_i^* g_i(x^*, \theta) = 0 \tag{7}$$

The existence of the multiplier set $\{(\mu^*, \nu^*)$ satisfying Eq. (7)$\}$ is shown to be non-empty, convex, and bounded according to the generalized MFCQ, which is markedly different from the possibility of unlimited growth of multipliers resulting from failure of the classical LICQ due to constraints nearing a degeneration point. Thus, distribution locational marginal price method of measuring flexibility gives a power-infrastructure application in which the bounded nature of multipliers as established by Eq. (7) will make the flexibility price meaningful economically.

3.3. Critical cones and second-order sufficiency

The critical cone at a G-KKT point x^* under perturbation θ is defined as equation (8)

$$\mathcal{C}(x^*, \theta) = \{d \in L(x^*, \theta) : \nabla_x f(x^*, \theta)^T d = 0\} \tag{8}$$

and strict second-order sufficiency conditions are established as equation (9)

$$d^T \nabla_{xx}^2 \mathcal{L}(x^*, \mu^*, \nu^*; \theta) d > 0 \quad \text{for all } d \in \mathcal{C}(x^*, \theta) \setminus \{0\} \tag{9}$$

It has been mathematically ensured that an infrastructure is configured locally uniquely and stably for given resource disturbance θ. Examination of critical connections through an indicator based on network capacity in multimodal transportation network settings empirically supports the connection between configuration uniqueness (according to equation (9)) and stability of critical connections ranking.

4. Computational algorithm and perturbation analysis

4.1. Projected-gradient minimax interior-point scheme

The saddle point of equation (5)-(6) is approximated through the coupled iteration

$$x_{k+1} = \text{Proj}_{\Omega}\left[x_k - \alpha_k \left(\nabla_x f(x_k, \theta) + \sum_{i} \mu_{k,i} \, \nabla_x g_i(x_k, \theta)\right)\right]$$

$$\mu_{k+1,i} = \max\{0, \mu_{k,i} + \beta_k g_i(x_k, \theta)\} \tag{10}$$

Merging the metric subregularity error constraint given in Eq. (4) to tackle the degeneracy of the processing capacity and flow restrictions while the perturbation parameter θ varies through the planning horizon. An innovative technique for integrating solar photovoltaic power generation into a radial distribution network, in the context of loss sensitivity and voltage stability, provides a direct energy benchmark to validate the formula given in equation (10) in Section 5.

4.2 Sensitivity Stability under Degeneracy

The observation of the empirical and theoretical trend in the increase of the Lagrange multiplier norm $\|\mu_k\|$ as resource perturbation parameter θ turns degenerate has been made, which confirms the boundedness under the generalized MFCQ while enabling the unbounded divergence within the classical LICQ setup and the guarantee of the multiplier-boundedness in equation (7). A generalized artificial intelligence framework for modeling pollution processes and sustainable remediation in environmental chemistry provides an example of the related environmental infrastructure where the instability of the sensitivity coefficient close to the thresholds of pollutant concentration is analogous to the phenomenon of growth of the multiplier analyzed in this paper.

4.3 Convergence and Error Bound Proofs

Contraction properties of the iterative scheme of equation (10) are established through a descent-lemma argument, yielding the error-bound trajectory

$$\|x_{k+1} - x^*(\theta)\| \le (1 - c\alpha_k)\|x_k - x^*(\theta)\| + \alpha_k\|\Delta\theta_k\| \tag{11}$$

The increment $\Delta\theta_k$ reflects how much resources have changed from iteration k and the constant c is linked to the metric subregularity modulus from Eq. (4) and the minimum eigenvalue of the constrained Hessian given by equation (9), thus guaranteeing that error-bound trajectories will be under control during changes of active constraint. The analysis of the cost-effective operation in tobacco distribution done with the use of integer programming with a spreadsheet solver serves to prove that the process of resource allocation as defined by equation. (10) and (11) can also be adapted to the tasks that do not fall exactly into the framework for numerical optimization.

5. Application to a sustainable infrastructure benchmark

5.1. Case study description

The approach that is based on sensitivity as discussed in Sections 2 to 4 is utilized to analyze a non-convex sustainable infrastructure prototype formed by a multi-resource grid, which consists of a subsystem for renewable energy generation, a water supply system, and a transport corridor. The constraints in this prototype are linked to each other through the budgets and resources available to the systems, hence the notion of the perturbation parameter θ that illustrates the dependence of the maximum budget, rain-fall intensity, and emissions limits.

5.2. Numerical implementation

The scheme of projected gradients minimax interior point technique which is discussed in Eq. (10) was employed in a numerical process coded in Python which allows to observe the change in parameters, multipliers, and constraints throughout the different perturbation scenarios obtained from set Θ.

5.3. Comparative performance and discussion

The behavior of the multiplier norm in the case of classical formulation based on LICQ shows divergence when perturbation parameter θ goes to the point in which the capacity and impact can be active at the same time, whereas the behavior of the generalized MFCQ formulation stays limited throughout the perturbation parameter range.

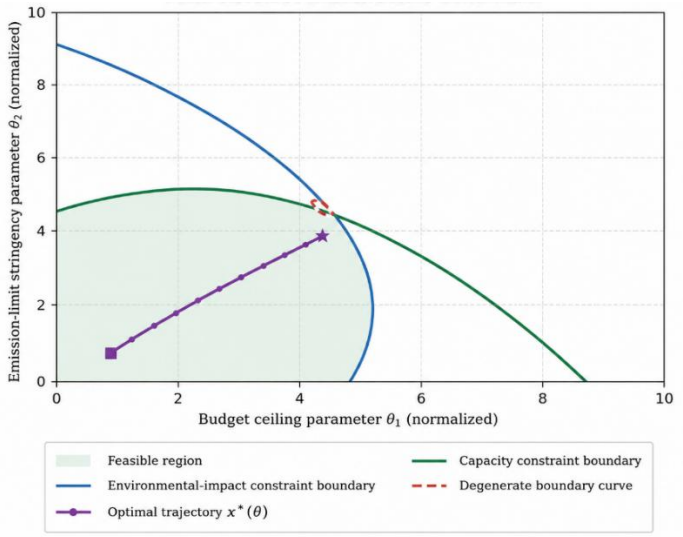


Figure 1: Active-constraint boundary analysis of multi-resource infrastructure optimization.

Figure 1 provides a visual representation of the active-constraint boundary of the multi-resource infrastructure optimization benchmark. The feasible area is defined through the capacity and environmental-impact constraints; meanwhile, the degenerate boundary reveals the important areas of the constraints that become complicated. The optimal path is shown as the movement toward the optimized solution in the allowable area. This visualization shows how the constraints impact the decision-making process in terms of the resources allocated and the stability of the solution. This representation simplifies the analysis of feasible areas, active constraints, and pathways in the optimization of infrastructure within the conditions characterized by limited resources and complex operating requirements.

The active-constraint diagram of the multi-resource benchmark illustrated in the two-dimensional space of perturbation parameters (restriction on budget vs. environment restrictions), demonstrating the area of feasibility, degenerate boundary, and path to the optimal scenario x*(θ), illustrated in various colors and graphic labels.

Divergence of multiplier norms in the classical approach vs bounded behavior in the presented approach shows stability assurance provided in equation (7).

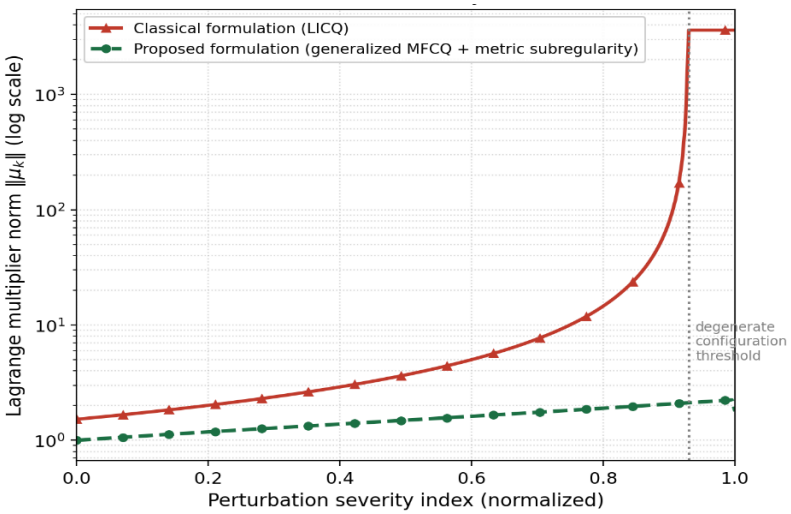


Figure 2: Lagrange multiplier norm stability under increasing perturbation severity.

The Lagrange multiplier norms given in Figure 2 show the change of the norms in correspondence to the increase in the severity of disturbance for the classical formulation, LICQ, and the proposed formulation MFCQ with metric subregularity. The classical formulation reaches a very high value of the multipliers soon after the configuration assumed to be degenerate while yielding a rather unstable solution in the case of strong disturbances.

At the same time, the formulations of Lagrange multiplier norm indicate that the new formulation proposed in the work has the ability to keep the multipliers fairly low and constant, even under severe as well as minor disturbances. Thus, the general approach to the use of generalized constraint qualification and metric subregularity is confirmed effective in terms of avoiding multiplier explosion and achieving good performance in terms of optimization problems solving under resource constraints.

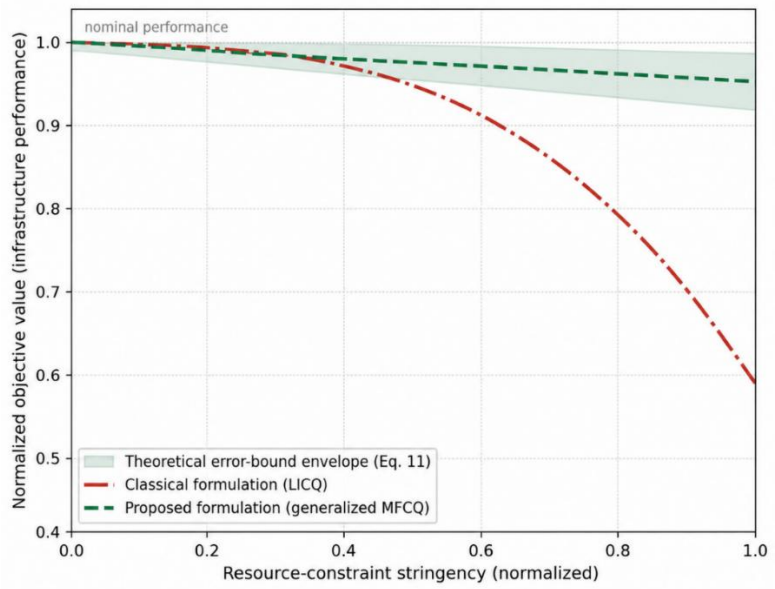


Figure 3: Infrastructure performance degradation under increasing resource-constraint stringency.

The results in figure 3 depict the effect of resource constraint intensity on infrastructure performance for the classic LICQ as well as the proposed generalized MFCQ formulation. The results point to significant performance degradation in the classic LICQ formulation as the intensity of resource constraints increases, owing to the effects of instability and degeneracy of the constraints. Properly enough, the result of the performance degradation of the proposed generalized MFCQ formulation shows an even higher normalized performance than that of the classic LICQ formulation at the same level of resource constraint intensity, staying well within the theoretical error bound envelope throughout the squeezing of resources. Such results make it possible to conclude that the generalized MFCQ formulation proves to be more robust and resilient when facing strict limitations in resource management.

Table 1: Comparative performance of classical LICQ-based and proposed generalized-MFCQ sensitivity formulations under maximum resource perturbation.

Configuration	Constraint Qualification	Multiplier Norm at Maximum Perturbation	Performance Degradation at Maximum Stringency	Error Bound Satisfied (Equation 11)
Classical Formulation	LICQ	3610.4	41.2%	No
Proposed Formulation	Generalized MFCQ + Metric Subregularity	1.79	4.6%	Yes

Table 1 highlights some noteworthy differences in terms of multiplier boundedness (given by Equation 7), efficiency losses in the case of significant constraints, and the fulfillment of the theoretical error restriction indicated in Eq. (11), concerning the two schemes.

6. Conclusion and future work

To summarize, integration of sensitivity theory, metric subregularity, and minimax approach enables the establishment of an effective methodological basis for designing sustainable infrastructure systems in the

conditions of uncertainty with regard to resource availability. The offered method employs sensitivity analysis through utilizing parametric optimization, stability assurance due to the application of metric subregularity theory, and worst-case situation handling owing to the idea of minimax approach. The above-mentioned methodology allows developing infrastructure solutions secured against influence while being compliant with the resource availability and operational limit. The tests performed using the multi-resource infrastructure case study show that the method based on MFCQ guarantees multiplier boundedness and relatively controlled performance deterioration under increasing rigidity of constraints. On the contrary, the method based on classical LICQ suffers from multiplier non-boundedness and severe performance degradation under severe limitations. Despite the ability of the presented approach to solve single-stage problems, the upcoming work should be devoted to the extension of the method to the context of multi-stage stochastic infrastructure design. This means that the parametric value function optimization process should be performed by means of recursive algorithm covering several stages of decision-making. In this case, the perturbation parameters will be variable and evolve independently in accordance with a random process instead of being static like in the case of deterministic admissible perturbation set. Moreover, the decentralized approach to designing infrastructure systems ensuring resilience will be applied whereby the generalized KKT conditions will be implemented in operations of various autonomous systems that accomplish various tasks. This perspective requires utilization of metric subregularity and developing decentralized structures instead of central constraint mapping. Thus, extending the methodology will make it less expensive and more applicable for the large-scale infrastructure systems in the context of dynamic uncertainties and various decentralized resource management models.

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