Equivalence of local-and global-best approximations, a simple stable local commuting projector, and optimal hp approximation estimates in H(div)

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Equivalence of local- and global-best approximations, a simple stable local commuting projector, and optimal hp approximation estimates in $\boldsymbol{H}(\mathrm{div})$*

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Abstract

Given an arbitrary function in $\boldsymbol{H}(\mathrm{div})$, we show that the error attained by the global-best approximation by $\boldsymbol{H}(\mathrm{div})$-conforming piecewise polynomial Raviart–Thomas–Nédélec elements under additional constraints on the divergence and normal flux on the boundary, is, up to a generic constant, equivalent to the sum of independent local-best approximation errors over individual mesh elements, without constraints on the divergence or normal fluxes. The generic constant only depends on the shape-regularity of the underlying simplicial mesh, the space dimension, and the polynomial degree of the approximations. The analysis also gives rise to a stable, local, commuting projector in $\boldsymbol{H}(\mathrm{div})$, delivering an approximation error that is equivalent to the local-best approximation. We next present a variant of the equivalence result, where robustness of the constant with respect to the polynomial degree is attained for unbalanced approximations. These two results together further enable us to derive rates of convergence of global-best approximations that are fully optimal in both the mesh size h and the polynomial degree p, for vector fields that only feature elementwise the minimal necessary Sobolev regularity. We finally show how to apply our findings to derive optimal a priori hp-error estimates for mixed and least-squares finite element methods applied to a model diffusion problem.

Keywords. best approximation, piecewise polynomial, localization, $\boldsymbol{H}(\mathrm{div})$ Sobolev space, Raviart–Thomas–Nédélec space, minimal regularity, optimal error bound, commuting projector, mixed finite element method, least-squares method, a priori error estimate.

1 Introduction

Interpolation operators that approximate a given function with weak gradient, curl, or divergence by a piecewise polynomial of degree p are fundamental in numerical analysis. Typically, this is done over a computational domain Ω covered by a mesh $\mathcal{T}$ with characteristic size h. The canonical interpolation operators associated with the degrees of freedom commute with the appropriate differential operators and they are projectors, i.e., they leave the interpolated function invariant if it is already a piecewise polynomial; the term "commuting projector" is commonly used in the literature in such a case. They are also local (defined independently on each element K of the mesh $\mathcal{T}$) and they lead to optimal approximation error bounds with respect to the mesh size h. However, the canonical interpolation operators have two main deficiencies. Firstly, they can act on a given function only if it possesses more regularity beyond the minimal H^1, $\boldsymbol{H}(\mathrm{div})$, or $\boldsymbol{H}(\mathrm{curl})$. And secondly, they are not well-suited to derive approximation error bounds that are optimal in the polynomial degree p.

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1.1 Interpolation operators and hp-approximation

The projection-based interpolation operators, see Demkowicz and Buffa [18], Demkowicz [17], and the references therein, lead to *optimal approximation properties* in the *mesh size* h and *quasi-optimal approximation properties* in the *polynomial degree* p (up to logarithmic factors). They were derived under a conjecture of existence of commuting and polynomial-preserving extension operators from the boundary of the given element K to its interior which was later established by Demkowicz *et al.* in [19, 20, 21]; the approximation results are summarized in [21, Theorem 8.1]. Thus, these operators essentially lift the second drawback of the canonical interpolation operators described above (up to logarithmic factors), while still being local commuting projectors. However, they again require more regularity beyond the minimal H^1, $\boldsymbol{H}(\mathrm{div})$, or $\boldsymbol{H}(\mathrm{curl})$.

In the particular case of $\boldsymbol{H}(\mathrm{div})$, which constitutes the focus of the present work, the normal component of the interpolate on each mesh face is fully dictated by the normal component of the interpolated function on that face, which requires $\boldsymbol{H}^s(\mathrm{div})$ regularity with $s > 0$, which is slightly more than $\boldsymbol{H}(\mathrm{div})$. Some further refinements can be found in Bespalov and Heuer [6] and Ern and Guermond [26]. Recently, a local commuting projector that has *optimal p-approximation properties* (does not feature the logarithmic factors) has been devised by Melenk and Rojik in [36]. To define the projector, though, higher regularity is needed, with in particular $\boldsymbol{H}^s(\mathrm{div})$, $s \geq 1$, in the case of interest here.

The issue of constructing (quasi-)interpolation projectors under the minimal regularities H^1, $\boldsymbol{H}(\mathrm{div})$, and $\boldsymbol{H}(\mathrm{curl})$ has been addressed before, cf., e.g., Clément [15], Scott and Zhang [44], and Bernardi and Girault [4] in the H^1 case, Nochetto and Stamm [38] in the $\boldsymbol{H}(\mathrm{div})$ case, and Bernardi and Hecht [5] in the $\boldsymbol{H}(\mathrm{curl})$ case; see also the references therein. Stability and h-optimal approximation estimates in any L^p-norm, $1 \leq p \leq \infty$, has recently been achieved by Ern and Guermond in [25] in a unified setting for a wide range of finite elements encompassing the whole discrete de Rham sequence. The arguments used in [25] are somewhat different from those in the previous references: a projection onto the fully discontinuous (broken) piecewise polynomial space is applied first, followed by an averaging operator to ensure the appropriate H^1, $\boldsymbol{H}(\mathrm{div})$, or $\boldsymbol{H}(\mathrm{curl})$ trace continuity. Unfortunately, all of the quasi-interpolation projectors mentioned in this paragraph do not commute with the appropriate differential operators and, moreover, they are only shown to be optimal in h but not in p.

1.2 Stable local commuting projectors under minimal regularity

Constructing projectors applicable under the *minimal regularities* H^1, $\boldsymbol{H}(\mathrm{div})$, and $\boldsymbol{H}(\mathrm{curl})$ that would in addition be *commuting*, *stable*, and *locally defined* represents a long-standing effort. Stability, commutativity, and the projection property were obtained by Christiansen and Winther in [14] by composing the canonical interpolation operators with mollification, following some earlier ideas in particular from Schöberl [42, 43], cf. also Ern and Guermond [24] for a shrinking technique avoiding the need of extensions outside of the domain and Licht [34] for essential boundary conditions only prescribed on a part of the boundary of Ω. These operators are, however, not locally defined. This last remaining issue was finally remedied in [31], where a patch-based construction resembling that of the Clément operator is introduced. However, no approximation properties are discussed, and stability is achieved only in the graph space of the appropriate differential operator, e.g., $\boldsymbol{H}(\mathrm{div})$, but not in $\boldsymbol{L}^2$ for the case of interest here.

1.3 Equivalence of local-best and global-best approximations

In a seemingly rather unconnected recent result, Veeser [45] showed that the error in the *best approximation* of a given scalar-valued function in H^1 by *continuous* piecewise polynomials is *equivalent* up to a generic constant to that by *discontinuous* piecewise polynomials. This result is termed equivalence of global- and local-best approximations. A predecessor result in the lowest-order case $p = 1$ and up to data oscillation can be easily deduced from Carstensen *et al.* [12, Theorem 2.1 and inequalities (3.2), (3.5), and (3.6)], see also the references therein; equivalences between approximations by different numerical methods are studied in [12]. A similar result is also given in Aurada *et al.* [1, Proposition 3.1], and an improvement of the dependence of the equivalence constant on the polynomial degree in two space dimensions is developed in [11, Theorem 4].

This equivalence result might be surprising at a first glance, since the local-best error is clearly smaller than the global-best one. The twist comes from the fact that any H^1 function is continuous in the sense of traces, so one does not gain in approximating it by discontinuous piecewise polynomials.

For finite element discretizations of coercive problems, this result in particular allows one to obtain estimates by a direct application of the Deny-Lions/Bramble-Hilbert lemma that does not require invoking an additional conforming and locally stable interpolation operator; see Gudi [32] or Carstensen and Schedensack [13] for examples of tools sharing the same spirit in a priori error analysis. Another important application is in approximation classes in a-posteriori-based convergence and optimality, cf. [45].

1.4 Main results of the manuscript

Our main results can be divided into three parts.

1) A simple stable local commuting projector defined under the minimal $\boldsymbol{H}(\mathrm{div})$ regularity We define an interpolation operator on the entire $\boldsymbol{H}(\mathrm{div})$ space that is a projector, enjoys a commuting property with the divergence operator, is locally defined over patches of elements, and is stable in $\boldsymbol{L}^2$ up to a *hp* data oscillation term for the divergence. It also takes into account essential (no-flux) boundary conditions on only a part of the computational domain and it achieves, on each element, an error equivalent to local-best errors over a patch of neighbouring elements. All these results are summarized in Definition 3.1 and Theorem 3.2 below. Our main tool for defining the projector is the *equilibrated flux reconstruction*. This technique has been traditionally used in *a posteriori* error analysis of *primal* finite element methods derived from H^1-formulations, see Destuynder and Métivet [22], Luce and Wohlmuth [35], Braess and Schöberl [9], Ern and Vohralík [28, 29], Becker *et al.* [3], and the references therein. We now employ it here in the context of *a priori* error analysis of *dual* approximations in $\boldsymbol{H}(\mathrm{div})$.

2) Equivalence of local- and global-best approximations in $\boldsymbol{H}(\mathrm{div})$ under minimal regularity In Theorem 3.3, we show that the *global* best-approximation error defined in (3.10) is, up to a generic constant, *equivalent* to the *local*-best approximation errors defined by elementwise minimizations (3.11). This actually results from the properties of the above projector. This extends the results of [1, 11, 12, 45] to the $\boldsymbol{H}(\mathrm{div})$ case, where we are importantly able to remove *constraints* on *both* the *normal trace* inter-element continuity and the *divergence*.

3) Optimal *hp*-approximation estimates in $\boldsymbol{H}(\mathrm{div})$ Our third main result is Theorem 3.6 where we derive *hp-approximation estimates*. These estimates feature the following four properties: i) they request *no global regularity* of the approximated function $\boldsymbol{v}$ beyond $\boldsymbol{H}(\mathrm{div})$; ii) only the *minimal local (elementwise)* $\boldsymbol{H}^s$*-regularity*, $s \geq 0$, is needed; iii) the convergence rates are *fully optimal* in both the *mesh-size* h and the *polynomial degree* p, in particular featuring no logarithmic factor of the polynomial degree p; iv) *no higher-order norms of the divergence* of $\boldsymbol{v}$ appear in the bound whenever $s \geq 1$. This improves on [18, 17] in removing the suboptimality with respect to the polynomial degree, on [18, 17, 36] in reducing the regularity requirements, and on approximations using Clément-type operators in removing the need for regularity assumptions over the (overlapping) elemental patches while reducing it instead to (nonoverlapping) elements.

1.5 Applications to mixed finite element and least-squares mixed finite element methods

The above results can be immediately turned into fully optimal *hp a priori error estimates* for two popular classes of numerical methods for second-order elliptic partial differential equations, the mixed finite element methods and the least-squares methods, as we show in Lemmas 6.1–6.3. Note also that an immediate application of the commuting projector of Definition 3.1 in the context of mixed finite elements is the construction of a *Fortin operator* under the *minimal* $\boldsymbol{H}(\mathrm{div})$ *regularity*.

1.6 Organization of the manuscript

The rest of the manuscript is organized as follows. In Section 2, we introduce the setting and notation. In Section 3, we state our main results, whereas Sections 4 and 5 are concerned with their proofs and Section 6 with the application. A result on polynomial-degree-robust equivalence between constrained and unconstrained best approximations in $\boldsymbol{H}(\mathrm{div})$ on a simplex is presented in Appendix A; it is of independent interest. We present our results in two or three space dimensions only since this is the current limitation of Lemma 4.4, which hinges on [16] and [21]. Lemma 4.4, with the involved constant independent of the polynomial degree p, is only crucial for Theorem 3.6; the other results actually hold in arbitrary space dimension. Variable polynomial degrees can be taken into account by proceeding as in, e.g., [23]. We avoid it here for the sake of clarity of exposition.

2 Setting and notation

2.1 Domain Ω, space $\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$, and simplicial mesh $\mathcal{T}$

Let $\Omega \subset \mathbb{R}^d$ for $d \in \{2,3\}$ be an open, bounded, connected polygon or polyhedron with Lipschitz boundary Γ. Let $\mathcal{T}$ be a given conforming, simplicial, shape-regular, and possibly locally refined mesh of Ω, i.e. $\overline{\Omega} = \cup_{K\in\mathcal{T}} K$, where any K is a closed simplex and the intersection of two different simplices is either an empty set or their common vertex, edge, or face. Let Γ_{D} be a (possibly empty) closed subset of Γ, and let $\Gamma_{\mathrm{N}} \coloneqq \Gamma \setminus \Gamma_{\mathrm{D}}$ be its (relatively open) complement in Γ, with the assumption that $\mathcal{T}$ matches Γ_{D} and Γ_{N} in the sense that every boundary face of the mesh $\mathcal{T}$ is fully contained either in Γ_{D} or in $\overline{\Gamma_{\mathrm{N}}}$. Let $\boldsymbol{L}^2(\Omega) \coloneqq L^2(\Omega;\mathbb{R}^d)$, and $\boldsymbol{H}(\mathrm{div},\Omega) \coloneqq \{\boldsymbol{v} \in \boldsymbol{L}^2(\Omega),\ \nabla{\cdot}\boldsymbol{v} \in L^2(\Omega)\}$. Furthermore, we define the space $\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega) \coloneqq \{\boldsymbol{v} \in \boldsymbol{H}(\mathrm{div},\Omega),\ \boldsymbol{v}{\cdot}\boldsymbol{n} = 0 \text{ on } \Gamma_{\mathrm{N}}\}$, where $\boldsymbol{v}{\cdot}\boldsymbol{n} = 0$ on Γ_{N} means that $\langle \boldsymbol{v}{\cdot}\boldsymbol{n}, \varphi\rangle_\Gamma = 0$ for all functions $\varphi \in H^1(\Omega)$ that have vanishing trace on Γ_{D}; here $\langle \boldsymbol{v}{\cdot}\boldsymbol{n}, \varphi\rangle_\Gamma \coloneqq \int_\Omega [\boldsymbol{v}{\cdot}\nabla\varphi + (\nabla{\cdot}\boldsymbol{v})\varphi]$. For an open subset $\omega \subset \Omega$, let $\boldsymbol{L}^2(\omega) \coloneqq L^2(\omega;\mathbb{R}^d)$ and $\boldsymbol{H}(\mathrm{div},\omega) \coloneqq \{\boldsymbol{v} \in \boldsymbol{L}^2(\omega),\ \nabla{\cdot}\boldsymbol{v} \in L^2(\omega)\}$. We also denote by $(\cdot,\cdot)_\omega$ and $\|\cdot\|_\omega$ the L^2-inner product and norm for scalar- or vector-valued functions on ω. In the special case where $\omega = \Omega$, we drop the subscript, i.e. $(\cdot,\cdot) \coloneqq (\cdot,\cdot)_\Omega$ and $\|\cdot\| \coloneqq \|\cdot\|_\Omega$. The diameter of ω is denoted by h_ω, and its outward unit normal by $\boldsymbol{n}_\omega$.

2.2 Elements, vertices, faces, and patches of elements

For any mesh element $K \in \mathcal{T}$, its diameter is denoted by h_K, and we set $h \coloneqq \max_{K\in\mathcal{T}} h_K$. Let $\mathcal{V}_\Omega$ denote the set of interior vertices of $\mathcal{T}$, i.e. the vertices contained in Ω. Let $\mathcal{V}_\Gamma$ denote the set of vertices of $\mathcal{T}$ on the boundary Γ, and set $\mathcal{V} \coloneqq \mathcal{V}_\Omega \cup \mathcal{V}_\Gamma$. We divide $\mathcal{V}_\Gamma$ into two disjoint sets $\mathcal{V}_{\mathrm{D}}$ and $\mathcal{V}_{\mathrm{N}}$, where $\mathcal{V}_{\mathrm{D}}$ contains all vertices in Γ_{D} (recalling that Γ_{D} is assumed to be closed) and $\mathcal{V}_{\mathrm{N}}$ consists of all vertices in Γ_{N}. For each vertex $\boldsymbol{a} \in \mathcal{V}$, define the patch $\mathcal{T}_{\boldsymbol{a}} \coloneqq \{K \in \mathcal{T},\ \boldsymbol{a} \text{ is a vertex of } K\}$ and the corresponding open subdomain $\omega_{\boldsymbol{a}} \coloneqq \{\cup_{K\in\mathcal{T}_{\boldsymbol{a}}} K\}^\circ$. The piecewise affine Lagrange finite element basis function associated with a vertex $\boldsymbol{a} \in \mathcal{V}$ is denoted by $\psi_{\boldsymbol{a}}$. Let $\mathcal{F}$ denote the set of all $(d-1)$-dimensional faces of $\mathcal{T}$. By convention, we consider faces to be closed sets. For an element $K \in \mathcal{T}$, we denote the set of all faces of K by $\mathcal{F}_K$, and the set of all vertices of K by $\mathcal{V}_K$. For each interior vertex $\boldsymbol{a} \in \mathcal{V}_\Omega$, we let $\mathcal{F}_{\boldsymbol{a}}^{\mathrm{in}}$ denote the set of all faces that contain the vertex $\boldsymbol{a}$ (and thus do not lie on the boundary of $\omega_{\boldsymbol{a}}$). For boundary vertices $\boldsymbol{a} \in \mathcal{V}_\Gamma$, let $\mathcal{F}_{\boldsymbol{a}}^{\mathrm{in}}$ collect the faces that contain the vertex $\boldsymbol{a}$ but do not lie on the Dirichlet boundary Γ_D. The mesh shape-regularity parameter is defined as $\kappa_{\mathcal{T}} \coloneqq \max_{K\in\mathcal{T}} h_K/\varrho_K$, where ϱ_K is the diameter of the largest ball inscribed in K.

2.3 Piecewise polynomial and Raviart–Thomas–Nédélec spaces

Let $p \geq 0$ be a nonnegative integer. For $S \in \{K, F\}$, where $K \in \mathcal{T}$ is an element and $F \in \mathcal{F}$ is a face, we define $\mathcal{P}_p(S)$ as the space of all polynomials of total degree at most p on S. If $\widetilde{\mathcal{T}}$ denotes a subset of elements of $\mathcal{T}$, $\mathcal{P}_p(\widetilde{\mathcal{T}}) \coloneqq \{v_h \in L^2(\Omega),\ v_h|_K \in \mathcal{P}_p(K)\ \ \forall K \in \widetilde{\mathcal{T}}\}$ is the space of piecewise polynomials of degree at most p over $\widetilde{\mathcal{T}}$. Typically, $\widetilde{\mathcal{T}}$ will be either the whole mesh $\mathcal{T}$ or the vertex patch $\mathcal{T}_{\boldsymbol{a}}$ as defined above. We define the piecewise Raviart–Thomas–Nédélec space $\boldsymbol{RTN}_p(\mathcal{T}) \coloneqq \{\boldsymbol{\varsigma}_{\mathcal{T}} \in \boldsymbol{L}^2(\Omega),\ \boldsymbol{\varsigma}_{\mathcal{T}}|_K \in \boldsymbol{RTN}_p(K)\ \forall K \in \mathcal{T}\}$, where $\boldsymbol{RTN}_p(K) \coloneqq \mathcal{P}_p(K;\mathbb{R}^d) + \boldsymbol{x}\mathcal{P}_p(K)$ and $\mathcal{P}_p(K;\mathbb{R}^d)$ denotes the space of $\mathbb{R}^d$-valued functions defined on K with each component being a polynomial of degree at most p in $\mathcal{P}_p(K)$. Note that with this choice of notation, functions in the space $\boldsymbol{RTN}_p(\mathcal{T})$ do not necessarily belong to $\boldsymbol{H}(\mathrm{div},\Omega)$; thus, $\boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}(\mathrm{div},\Omega)$ is a proper subspace of $\boldsymbol{RTN}_p(\mathcal{T})$ which is classically characterized as those functions in $\boldsymbol{RTN}_p(\mathcal{T})$ having a continuous normal component across interior mesh faces. Moreover, $\boldsymbol{RTN}_p(\mathcal{T})$ is a subspace of $\boldsymbol{C}^1(\mathcal{T}) \coloneqq \{\boldsymbol{v} \in \boldsymbol{L}^2(\Omega),\ \boldsymbol{v}|_K \in \boldsymbol{C}^1(K) \text{ for all } K \in \mathcal{T}\}$, the space of piecewise (broken) first-order component-wise differentiable vector-valued fields over $\mathcal{T}$. To avoid confusion between piecewise smooth and globally smooth functions, we denote the elementwise gradient and the elementwise divergence by $\nabla_{\mathcal{T}}$ and by $\nabla_{\mathcal{T}}{\cdot}$, respectively.

2.4 L^2-orthogonal projection and elementwise canonical interpolant

For each polynomial degree $p \geq 0$, let $\Pi_{\mathcal{T}}^p\colon L^2(\Omega) \to \mathcal{P}_p(\mathcal{T})$ denote the L^2-orthogonal projection of order p. Similarly, let Π_F^p denote the L^2-orthogonal projection of order p on a face $F \in \mathcal{F}$, which maps $L^2(F)$ to $\mathcal{P}_p(F)$. Let $\boldsymbol{I}_{\mathcal{T}}^p\colon \boldsymbol{C}^1(\mathcal{T}) \to \boldsymbol{RTN}_p(\mathcal{T})$ be the *elementwise* canonical (Raviart–Thomas–Nédélec) interpolant. The domain of $\boldsymbol{I}_{\mathcal{T}}^p$ can be taken to be a (much) larger space than $\boldsymbol{C}^1(\mathcal{T})$, but not as large as piecewise $\boldsymbol{H}(\mathrm{div})$ fields; the present choice is sufficient for our purposes. For any $\boldsymbol{v} \in \boldsymbol{C}^1(\mathcal{T})$, the interpolant $\boldsymbol{I}_{\mathcal{T}}^p\boldsymbol{v}$ is defined separately on each element $K \in \mathcal{T}$ by the conditions

$$\begin{aligned} ((\boldsymbol{I}_{\mathcal{T}}^p\boldsymbol{v})|_K\cdot\boldsymbol{n}_K, q_K)_F &= (\boldsymbol{v}|_K\cdot\boldsymbol{n}_K, q_K)_F \quad && \forall q_K \in \mathcal{P}_p(F),\ \forall F \in \mathcal{F}_K, \\ (\boldsymbol{I}_{\mathcal{T}}^p\boldsymbol{v}, \boldsymbol{r}_K)_K &= (\boldsymbol{v}, \boldsymbol{r}_K)_K && \forall \boldsymbol{r}_K \in \mathcal{P}_{p-1}(K;\mathbb{R}^d), \end{aligned} \tag{2.1}$$

where $\boldsymbol{v}|_K\cdot\boldsymbol{n}_K$ denotes the normal trace of $\boldsymbol{v}|_K$, the restriction of $\boldsymbol{v}$ to K. Note that (2.1) implies that $((\boldsymbol{I}_{\mathcal{T}}^p\boldsymbol{v})|_K\cdot\boldsymbol{n}_K)|_F = \Pi_F^p((\boldsymbol{v}|_K\cdot\boldsymbol{n}_K)|_F)$ for all faces $F \subset \mathcal{F}_K$. A useful property of the operator $\boldsymbol{I}_{\mathcal{T}}^p$ is the commuting identity:

$$\nabla_{\mathcal{T}}\cdot(\boldsymbol{I}_{\mathcal{T}}^p\boldsymbol{v}) = \Pi_{\mathcal{T}}^p(\nabla_{\mathcal{T}}\cdot\boldsymbol{v}) \quad \forall \boldsymbol{v} \in \boldsymbol{C}^1(\mathcal{T}). \tag{2.2}$$

2.5 Spaces for patchwise equilibration

In the spirit of Braess *et al.* [8] and [28, 29, 27], we finally define the local mixed finite element spaces $\boldsymbol{V}_p(\omega_{\boldsymbol{a}})$ by

$$\boldsymbol{V}_p(\omega_{\boldsymbol{a}}) := \begin{cases} \{\boldsymbol{\varsigma}_{\boldsymbol{a}} \in \boldsymbol{RTN}_p(\mathcal{T}_{\boldsymbol{a}}) \cap \boldsymbol{H}(\mathrm{div};\omega_{\boldsymbol{a}}),\ \boldsymbol{\varsigma}_{\boldsymbol{a}}\cdot\boldsymbol{n}_{\omega_{\boldsymbol{a}}} = 0 \text{ on } \partial\omega_{\boldsymbol{a}}\} & \text{if } \boldsymbol{a} \in \mathcal{V}_\Omega \cup \mathcal{V}_{\mathrm{N}}, \\ \{\boldsymbol{\varsigma}_{\boldsymbol{a}} \in \boldsymbol{RTN}_p(\mathcal{T}_{\boldsymbol{a}}) \cap \boldsymbol{H}(\mathrm{div};\omega_{\boldsymbol{a}}),\ \boldsymbol{\varsigma}_{\boldsymbol{a}}\cdot\boldsymbol{n}_{\omega_{\boldsymbol{a}}} = 0 \text{ on } \partial\omega_{\boldsymbol{a}} \setminus \Gamma_{\mathrm{D}}^{\boldsymbol{a}}\} & \text{if } \boldsymbol{a} \in \mathcal{V}_{\mathrm{D}}, \end{cases} \tag{2.3}$$

where $\Gamma_{\mathrm{D}}^{\boldsymbol{a}}$ contains those boundary faces from Γ_{D} that share the vertex $\boldsymbol{a}$. In particular, we observe that when $\partial\omega_{\boldsymbol{a}} \cap \Gamma_{\mathrm{N}} \neq \emptyset$, then $\boldsymbol{\varsigma}_{\boldsymbol{a}}\cdot\boldsymbol{n} = 0$ on Γ_{N} for any $\boldsymbol{\varsigma}_{\boldsymbol{a}} \in \boldsymbol{V}_p(\omega_{\boldsymbol{a}})$. As a result of the above definitions, it follows that the zero extension to all of Ω of any $\boldsymbol{\varsigma}_{\boldsymbol{a}} \in \boldsymbol{V}_p(\omega_{\boldsymbol{a}})$ belongs to $\boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$.

3 Main results

This section collects our main results.

3.1 A simple stable local commuting projector in $\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$

We first construct a simple, local, and stable commuting projector defined over the entire $\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ that leads to an approximation error equivalent to the local-best approximation error.

Recall the definition of the broken Raviart–Thomas–Nédélec interpolant $\boldsymbol{I}_{\mathcal{T}}^p$ from (2.1) and that of the piecewise polynomial patchwise $\boldsymbol{H}(\mathrm{div};\omega_{\boldsymbol{a}})$-conforming spaces $\boldsymbol{V}_p(\omega_{\boldsymbol{a}})$ from (2.3). Recall also that zero extensions of elements of $\boldsymbol{V}_p(\omega_{\boldsymbol{a}})$ belong to $\boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$, and that $\psi_{\boldsymbol{a}}$ is the piecewise affine Lagrange finite element basis function associated with the vertex $\boldsymbol{a}$.

Definition 3.1 (A simple locally-defined mapping from $\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ to $\boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$)**.** *Let $\boldsymbol{v} \in \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ be arbitrary. Let $\boldsymbol{\tau}_{\mathcal{T}} \in \boldsymbol{RTN}_p(\mathcal{T})$ be defined elementwise by*

$$\boldsymbol{\tau}_{\mathcal{T}}|_K := \mathop{\arg\min}_{\substack{\boldsymbol{\varsigma}_K \in \boldsymbol{RTN}_p(K) \\ \nabla\cdot\boldsymbol{\varsigma}_K = \Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{v})}} \|\boldsymbol{v} - \boldsymbol{\varsigma}_K\|_K \qquad \forall K \in \mathcal{T}. \tag{3.1}$$

For each mesh vertex $\boldsymbol{a} \in \mathcal{V}$, let $\boldsymbol{\sigma}_{\boldsymbol{a}} \in \boldsymbol{V}_p(\omega_{\boldsymbol{a}})$ be defined by

$$\boldsymbol{\sigma}_{\boldsymbol{a}} := \mathop{\arg\min}_{\substack{\boldsymbol{\varsigma}_{\boldsymbol{a}} \in \boldsymbol{V}_p(\omega_{\boldsymbol{a}}) \\ \nabla\cdot\boldsymbol{\varsigma}_{\boldsymbol{a}} = \Pi_{\mathcal{T}}^p(\psi_{\boldsymbol{a}}\nabla\cdot\boldsymbol{v} + \nabla\psi_{\boldsymbol{a}}\cdot\boldsymbol{\tau}_{\mathcal{T}})}} \|\boldsymbol{\varsigma}_{\boldsymbol{a}} - \boldsymbol{I}_{\mathcal{T}}^p(\psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}})\|_{\omega_{\boldsymbol{a}}}. \tag{3.2}$$

Extending $\boldsymbol{\sigma}_{\boldsymbol{a}}$ from the $\omega_{\boldsymbol{a}}$ to the rest of Ω by zero, we define $P_{\mathcal{T}}^p(\boldsymbol{v}) \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ by

$$P_{\mathcal{T}}^p(\boldsymbol{v}) := \boldsymbol{\sigma}_{\mathcal{T}} := \sum_{\boldsymbol{a}\in\mathcal{V}} \boldsymbol{\sigma}_{\boldsymbol{a}}. \tag{3.3}$$

The justification that the construction of $P_{\mathcal{T}}^p(\boldsymbol{v})$ is well-defined is given in Section 4.1 below. The first step (3.1) considers the elementwise $\boldsymbol{L}^2$-norm local-best approximation that defines the *discontinuous piecewise RTN polynomial* $\boldsymbol{\tau}_{\mathcal{T}}$ closest to $\boldsymbol{v}$ under the divergence constraint. At this step, crucially, the minimal regularity $\boldsymbol{v} \in \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ is sufficient; note that we only work with $\boldsymbol{v}$ volume-wise and that no normal component of $\boldsymbol{v}$ on a face is requested to exist, in contrast to the common interpolation operators discussed in Section 1. Essentially, this step brings us into a piecewise polynomial setting, where we will stay henceforth, with $\boldsymbol{\tau}_{\mathcal{T}}$ being the best approximation on each mesh element $K \in \mathcal{T}$.

As $\boldsymbol{\tau}_{\mathcal{T}}$ from (3.1) is discontinuous from one mesh element to the other, the second step in (3.2) can be seen as *smoothing* $\boldsymbol{\tau}_{\mathcal{T}}$ over the vertex patch subdomains $\omega_{\boldsymbol{a}}$ to obtain an $\boldsymbol{H}(\mathrm{div};\omega_{\boldsymbol{a}})$-conforming approximation $\boldsymbol{\sigma}_{\boldsymbol{a}}$ with a suitably prescribed divergence. An important ingredient is the employment of the elementwise canonical Raviart–Thomas–Nédélec interpolant $\boldsymbol{I}^p_{\mathcal{T}}$ (this is well-justified, since the argument $\psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}}$ is a discrete object). The crucial role of $\boldsymbol{I}^p_{\mathcal{T}}$ is to decrease the order of $\psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}}$, which lies in $\boldsymbol{RTN}_{p+1}(\mathcal{T})$ because of the multiplication by the hat function $\psi_{\boldsymbol{a}}$, back to $\boldsymbol{RTN}_p(\mathcal{T})$. A similar construction below, see (5.3), will avoid the use of $\boldsymbol{I}^p_{\mathcal{T}}$ and will be crucial for our hp-optimal approximation estimates. Finally, in the third step (3.3), the approximations $\boldsymbol{\sigma}_{\boldsymbol{a}}$ are summed into $P^p_{\mathcal{T}}(\boldsymbol{v})$, thereby producing an $\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$-conforming piecewise polynomial from the RTN space of order p. The overall procedure is motivated by *equilibrated flux reconstructions* coming from a posteriori error estimation, as in [22, 9, 28]. Here we adapt those techniques to the purpose of a priori error analysis.

Our first main result, whose proof is postponed to Section 4, is the following.

Theorem 3.2 (Commutativity, projection, approximation, and stability of $P^p_{\mathcal{T}}$)**.** *Let a mesh $\mathcal{T}$ of Ω and a polynomial degree $p \geq 0$ be fixed. Then, the operator $P^p_{\mathcal{T}}$ from Definition 3.1 maps $\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ to $\boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ and*

$$\nabla{\cdot}P^p_{\mathcal{T}}(\boldsymbol{v}) = \Pi^p_{\mathcal{T}}(\nabla{\cdot}\boldsymbol{v}) \qquad \forall \boldsymbol{v} \in \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega), \tag{3.4}$$

$$P^p_{\mathcal{T}}(\boldsymbol{v}) = \boldsymbol{v} \qquad \forall \boldsymbol{v} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega). \tag{3.5}$$

Thus $P^p_{\mathcal{T}}$ is a projection from $\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ onto $\boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ such that the commuting property (3.4) is satisfied; this can be cast into the commuting diagram

$$\begin{array}{ccc} \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega) & \xrightarrow{\nabla\cdot} & L^2(\Omega) \\ \big\downarrow P^p_{\mathcal{T}} & & \big\downarrow \Pi^p_{\mathcal{T}} \\ \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega) & \xrightarrow{\nabla\cdot} & \mathcal{P}_p(\mathcal{T}) \end{array}.$$

Furthermore, for any $\boldsymbol{v} \in \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ and any $K \in \mathcal{T}$, we have the local approximation and stability bounds

$$\begin{aligned} &\|\boldsymbol{v} - P^p_{\mathcal{T}}(\boldsymbol{v})\|^2_K + \left[\frac{h_K}{p+1}\|\nabla{\cdot}(\boldsymbol{v} - P^p_{\mathcal{T}}(\boldsymbol{v}))\|_K\right]^2 \\ &\qquad \leq C \sum_{K' \in \mathcal{T}_K} \left\{ \min_{\boldsymbol{\varsigma}_{K'} \in \boldsymbol{RTN}_p(K')} \|\boldsymbol{v} - \boldsymbol{\varsigma}_{K'}\|^2_{K'} + \left[\frac{h_{K'}}{p+1}\|\nabla{\cdot}\boldsymbol{v} - \Pi^p_{\mathcal{T}}(\nabla{\cdot}\boldsymbol{v})\|_{K'}\right]^2 \right\}, \end{aligned} \tag{3.6}$$

$$\|P^p_{\mathcal{T}}(\boldsymbol{v})\|^2_K \leq C \sum_{K' \in \mathcal{T}_K} \left\{ \|\boldsymbol{v}\|^2_{K'} + \left[\frac{h_{K'}}{p+1}\|\nabla{\cdot}\boldsymbol{v} - \Pi^p_{\mathcal{T}}(\nabla{\cdot}\boldsymbol{v})\|_{K'}\right]^2 \right\}, \tag{3.7}$$

$$\|P^p_{\mathcal{T}}(\boldsymbol{v})\|^2_K + h^2_\Omega\|\nabla{\cdot}P^p_{\mathcal{T}}(\boldsymbol{v})\|^2_K \leq C \sum_{K' \in \mathcal{T}_K} \left\{ \|\boldsymbol{v}\|^2_{K'} + h^2_\Omega\|\nabla{\cdot}\boldsymbol{v}\|^2_{K'} \right\}, \tag{3.8}$$

where $\mathcal{T}_K := \cup_{\boldsymbol{a} \in \mathcal{V}_K}\mathcal{T}_{\boldsymbol{a}}$ are the neighboring elements of K, and recalling that h_Ω denotes the diameter of Ω. The constant C above only depends on the space dimension d, the shape-regularity parameter $\kappa_{\mathcal{T}}$ of $\mathcal{T}$, and the polynomial degree p.

Property (3.7) readily implies that $P^p_{\mathcal{T}}$ is globally $\boldsymbol{L}^2$-stable up to hp data oscillation of the divergence, since summing (3.7) over the mesh elements leads to

$$\|P^p_{\mathcal{T}}(\boldsymbol{v})\|^2 \leq C\left\{ \|\boldsymbol{v}\|^2 + \sum_{K \in \mathcal{T}} \left[\frac{h_K}{p+1}\|\nabla{\cdot}\boldsymbol{v} - \Pi^p_{\mathcal{T}}(\nabla{\cdot}\boldsymbol{v})\|_K\right]^2 \right\} \qquad \forall \boldsymbol{v} \in \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega). \tag{3.9a}$$

Similarly, from (3.8), we infer that $P^p_{\mathcal{T}}$ is $\boldsymbol{H}(\mathrm{div})$-stable, since

$$\|P^p_{\mathcal{T}}(\boldsymbol{v})\|^2 + h^2_\Omega\|\nabla{\cdot}P^p_{\mathcal{T}}(\boldsymbol{v})\|^2 \leq C\big[\|\boldsymbol{v}\|^2 + h^2_\Omega\|\nabla{\cdot}\boldsymbol{v}\|^2\big] \qquad \forall \boldsymbol{v} \in \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega). \tag{3.9b}$$

The projector $P^p_{\mathcal{T}}$ in Definition 3.1 and Theorem 3.2 improves on [14] in that the construction is *local*, and on [31] in that it is, up to data oscillation, *stable in $\boldsymbol{L}^2$* (i.e., with respect to $\|\boldsymbol{v}\|$), see (3.9a), rather than only in $\boldsymbol{H}(\mathrm{div})$ (i.e., with respect to $\big[\|\boldsymbol{v}\|^2 + h^2_\Omega\|\nabla{\cdot}\boldsymbol{v}\|^2\big]^{1/2}$), see (3.9b). We note more precisely that, for the divergence term, (3.7) improves the bound (5.2) of [31, Theorem 5.2] since, in particular, we have $\|\nabla{\cdot}\boldsymbol{v} - \Pi^p_{\mathcal{T}}(\nabla{\cdot}\boldsymbol{v})\|_K$ in place of $\|\nabla{\cdot}\boldsymbol{v}\|_K$, whereas (3.8) is similar to the combination of the bounds (5.2) and (5.3) of [31, Theorem 5.2]. Additionally, the terms with $\|\nabla{\cdot}\boldsymbol{v} - \Pi^p_{\mathcal{T}}(\nabla{\cdot}\boldsymbol{v})\|_K$ are of "*hp* data oscillation" type, containing the weight factors $h_K/(p+1)$, so that they tend optimally to zero for both $h \to 0$ and $p \to \infty$. The projection operator $P^p_{\mathcal{T}}$ defined here also satisfies the *commuting property* with the divergence operator (3.4), in contrast to [25].

3.2 Equivalence of local- and global-best approximations in $\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$

For any function $\boldsymbol{v} \in \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$, we consider the *global-best approximation error* $E_{\mathcal{T},p}(\boldsymbol{v})$ defined as the best approximation, in a weighted norm, from $\boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$, subject to a constraint on the divergence:

$$[E_{\mathcal{T},p}(\boldsymbol{v})]^2 := \min_{\substack{\boldsymbol{\varsigma}_{\mathcal{T}} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega) \\ \nabla{\cdot}\boldsymbol{\varsigma}_{\mathcal{T}} = \Pi^p_{\mathcal{T}}(\nabla{\cdot}\boldsymbol{v})}} \|\boldsymbol{v} - \boldsymbol{\varsigma}_{\mathcal{T}}\|^2_{\Omega} + \sum_{K \in \mathcal{T}} \left[\frac{h_K}{p+1}\|\nabla{\cdot}\boldsymbol{v} - \Pi^p_{\mathcal{T}}(\nabla{\cdot}\boldsymbol{v})\|_K\right]^2. \tag{3.10}$$

Note that the global minimization in (3.10) is subject to three constraints: the global minimizer $\boldsymbol{\varsigma}_{\mathcal{T}}$ has to have the normal trace continuous across the mesh faces, the normal trace on Γ_{N} equal to zero (whenever relevant), and the divergence equal to $\Pi^p_{\mathcal{T}}(\nabla{\cdot}\boldsymbol{v})$. We further consider the *local-best approximation errors* defined on each element $K \in \mathcal{T}$ by

$$[e_{K,p}(\boldsymbol{v})]^2 := \min_{\boldsymbol{\varsigma}_K \in \boldsymbol{RTN}_p(K)} \|\boldsymbol{v} - \boldsymbol{\varsigma}_K\|^2_K + \left[\frac{h_K}{p+1}\|\nabla{\cdot}\boldsymbol{v} - \Pi^p_{\mathcal{T}}(\nabla{\cdot}\boldsymbol{v})\|_K\right]^2. \tag{3.11}$$

Note that the local minimization in (3.11) is completely *constraint-free:* the local minimizer $\boldsymbol{\varsigma}_K$ is completely free on the faces of the mesh element K, including those in Γ_{N} (whenever relevant), and neither is a subject to any divergence constraint. Furthermore, since $\Pi^p_{\mathcal{T}}$ is the L^2-orthogonal projection onto the broken polynomial space $\mathcal{P}_p(\mathcal{T})$, we have $\|\nabla{\cdot}\boldsymbol{v} - \Pi^p_{\mathcal{T}}(\nabla{\cdot}\boldsymbol{v})\|_K = \min_{q \in \mathcal{P}_p(K)} \|\nabla{\cdot}\boldsymbol{v} - q\|_K$. Thus the local approximation errors $e_{K,p}(\boldsymbol{v})$ involve the local-best approximation errors in $\boldsymbol{L}^2$ plus a weighted L^2 best approximation error of the divergence.

In a direct consequence of Theorem 3.2, we now show that the global-best error $E_{\mathcal{T},p}(\boldsymbol{v})$ is in fact *equivalent* to the root-mean square sum of the local-best errors $e_{K,p}(\boldsymbol{v})$ over all elements of the mesh. This may seem surprising at a first sight, since the latter might initially seem to be (much) smaller.

Theorem 3.3 (Equivalence of local- and global-best approximations)**.** *There exists a constant C depending only on the space dimension d, the shape-regularity parameter $\kappa_{\mathcal{T}}$ of $\mathcal{T}$, and the polynomial degree $p \geq 0$, such that, for any $\boldsymbol{v} \in \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$,*

$$[E_{\mathcal{T},p}(\boldsymbol{v})]^2 \leq C \sum_{K \in \mathcal{T}} [e_{K,p}(\boldsymbol{v})]^2 \leq C\,[E_{\mathcal{T},p}(\boldsymbol{v})]^2. \tag{3.12}$$

Proof. The second inequality in (3.12) follows immediately from the definitions in (3.10) and (3.11): indeed, the global minimization set is (much) smaller than the local ones. To prove the first inequality, consider an arbitrary function $\boldsymbol{v} \in \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$. Then Theorem 3.2 shows that the projection $P^p_{\mathcal{T}}(\boldsymbol{v}) \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ satisfies the constraints of the global minimization set in (3.10) due to its commuting property (3.4). Therefore, it suffices to pick the function $P^p_{\mathcal{T}}(\boldsymbol{v})$ from the minimization set, sum the bound in the local approximation property (3.6) over all mesh elements, and invoke the shape-regularity of the mesh which implies that the number of neighbors a mesh cell can have is uniformly bounded from above. □

Remark 3.4 (Necessity of the divergence error terms)**.** Although the scaled divergence terms $\frac{h_K}{p+1}\|\nabla{\cdot}\boldsymbol{v} - \Pi^p_{\mathcal{T}}(\nabla{\cdot}\boldsymbol{v})\|_K$ take an identical form in both $E_{\mathcal{T},p}(\boldsymbol{v})$ and $e_{K,p}(\boldsymbol{v})$, they cannot be removed from the local contributions $e_{K,p}(\boldsymbol{v})$. Otherwise, it would be possible to choose a sequence of functions $\boldsymbol{v}$ in $\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ approaching a function $\boldsymbol{\tau}_{\mathcal{T}} \in \boldsymbol{RTN}_p(\mathcal{T})$ but $\boldsymbol{\tau}_{\mathcal{T}} \notin \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ such that the middle term in (3.12) would tend to zero, but $E_{\mathcal{T},p}(\boldsymbol{v})$ would remain uniformly bounded away from zero.

Remark 3.5 (Equivalence with constraint on the right-hand side)**.** Theorem 3.3 also straightforwardly implies the slightly weaker property

$$\begin{aligned}[E_{\mathcal{T},p}(\boldsymbol{v})]^2 &\leq C \sum_{K \in \mathcal{T}} \left\{ \min_{\substack{\boldsymbol{\varsigma}_K \in \boldsymbol{RTN}_p(K) \\ \nabla{\cdot}\boldsymbol{\varsigma}_K = \Pi^p_{\mathcal{T}}(\nabla{\cdot}\boldsymbol{v})|_K}} \|\boldsymbol{v} - \boldsymbol{\varsigma}_K\|^2_K + \left[\frac{h_K}{p+1}\|\nabla{\cdot}\boldsymbol{v} - \Pi^p_{\mathcal{T}}(\nabla{\cdot}\boldsymbol{v})\|_K\right]^2 \right\} \\ &\leq C\,[E_{\mathcal{T},p}(\boldsymbol{v})]^2\end{aligned}$$

with the same constant C, where the minimization problems in the middle term include a constraint on the divergence to mirror the divergence constraint in $E_{\mathcal{T},p}(\boldsymbol{v})$.

3.3 Optimal-order hp-approximation estimates in $\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathbf{div},\Omega)$

We finally focus on functions with some additional elementwise regularity. For any $s \geq 0$ and any mesh element $K \in \mathcal{T}$, let $\boldsymbol{H}^s(K)$ denote the space of vector-valued fields in $\boldsymbol{L}^2(K)$ with each component in $H^s(K)$. Recall the definition (3.10) of $E_{\mathcal{T},p}(\boldsymbol{v})$. Our third and last main result, whose proof is postponed to Section 5, delivers *hp-optimal* convergence rates for vector fields in $\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ with the *minimally* necessary additional *elementwise* $\boldsymbol{H}^s(K)$*-regularity.*

Theorem 3.6 (hp-optimal approximation estimates under minimal $\boldsymbol{H}^s(K)$-regularity)**.** *Let $s \geq 0$ and let $\boldsymbol{v} \in \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ be such that*

$$\boldsymbol{v}|_K \in \boldsymbol{H}^s(K) \quad \forall K \in \mathcal{T}.$$

Let the polynomial degree $p \geq 0$. Then there exists a constant C, depending only on the regularity exponent s, the space dimension d, and the shape-regularity parameter $\kappa_{\mathcal{T}}$ of $\mathcal{T}$, such that

$$[E_{\mathcal{T},p}(\boldsymbol{v})]^2 \leq C\bigg\{\sum_{K\in\mathcal{T}}\Big[\frac{h_K^{\min(s,p+1)}}{(p+1)^s}\|\boldsymbol{v}\|_{\boldsymbol{H}^s(K)}\Big]^2 + \delta_{s<1}\Big[\frac{h_K}{p+1}\|\nabla{\cdot}\boldsymbol{v}\|_K\Big]^2\bigg\}, \tag{3.13}$$

where $\delta_{s<1} \coloneqq 1$ if $s < 1$ and $\delta_{s<1} \coloneqq 0$ if $s \geq 1$.

Notice that the above generic constant C is independent of p and that the bound (3.13) is optimal with respect both the mesh size h and the polynomial degree p for arbitrary regularity index $s \geq 0$.

4 Proof of Theorem 3.2 (commutativity, projection, approximation, and stability of $P_{\mathcal{T}}^p$)

The proof of Theorem 3.2 is split into several parts. First, in Section 4.1, we analyse essential properties of the construction of the mapping $P_{\mathcal{T}}^p$ from Definition 3.1. We next establish the commuting property (3.4) in Section 4.2. Then, in Section 4.3, we prove the statement (3.6) on the approximation properties of $P_{\mathcal{T}}^p$. This is the most technical part of the proof. Finally, in Section 4.4, we conclude by proving the remaining three statements (3.5), (3.7), and (3.8) (the projection property, $\boldsymbol{L}^2$ stability, and $\boldsymbol{H}(\mathrm{div})$ stability).

4.1 Justification of the construction of $P_{\mathcal{T}}^p$

We start by showing that the operator $P_{\mathcal{T}}^p$ of Definition 3.1 is well-defined on $\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$. Recall the notation from Section 2.2.

Lemma 4.1 (Discrete weak divergence of $\boldsymbol{L}^2$-projection)**.** *For any function $\boldsymbol{v} \in \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$, let $\boldsymbol{\tau}_{\mathcal{T}}$ be defined elementwise in* (3.1)*. Then*

$$(\nabla{\cdot}\boldsymbol{v},\psi_{\boldsymbol{a}})_{\omega_{\boldsymbol{a}}} + (\boldsymbol{\tau}_{\mathcal{T}},\nabla\psi_{\boldsymbol{a}})_{\omega_{\boldsymbol{a}}} = 0 \quad \forall \boldsymbol{a} \in \mathcal{V}_\Omega \cup \mathcal{V}_{\mathrm{N}}. \tag{4.1}$$

Proof. First, observe that for any vertex $\boldsymbol{a} \in \mathcal{V}_\Omega \cup \mathcal{V}_{\mathrm{N}}$, the hat function $\psi_{\boldsymbol{a}}$ belongs to $H^1_{\Gamma_{\mathrm{D}}}(\Omega)$ owing to the conformity of $\mathcal{T}$ with respect to the Dirichlet and Neumann boundary sets. Therefore, $(\nabla{\cdot}\boldsymbol{v},\psi_{\boldsymbol{a}})_{\omega_{\boldsymbol{a}}} + (\boldsymbol{v},\nabla\psi_{\boldsymbol{a}})_{\omega_{\boldsymbol{a}}} = 0$, where we use the fact that $\omega_{\boldsymbol{a}}$ is the support of $\psi_{\boldsymbol{a}}$. Since $\nabla\psi_{\boldsymbol{a}}$ is a constant vector on each element K, the Euler–Lagrange equations for (3.1) imply that

$$(\boldsymbol{\tau}_{\mathcal{T}},\nabla\psi_{\boldsymbol{a}})_K = (\boldsymbol{v},\nabla\psi_{\boldsymbol{a}})_K \qquad \forall K \in \mathcal{T}_{\boldsymbol{a}}. \tag{4.2}$$

Consequently, $(\boldsymbol{\tau}_{\mathcal{T}},\nabla\psi_{\boldsymbol{a}})_{\omega_{\boldsymbol{a}}} = (\boldsymbol{v},\nabla\psi_{\boldsymbol{a}})_{\omega_{\boldsymbol{a}}}$, and (4.1) follows. □

We now show that the local minimization problems (3.2) give well-defined local contributions $\boldsymbol{\sigma}_{\boldsymbol{a}}$.

Lemma 4.2 (Existence and uniqueness of local problems (3.2))**.** *For each vertex $\boldsymbol{a} \in \mathcal{V}$, there exists a unique $\boldsymbol{\sigma}_{\boldsymbol{a}} \in \boldsymbol{V}_p(\omega_{\boldsymbol{a}})$ satisfying* (3.2)*.*

Proof. The minimization problem (3.2) is equivalent to a mixed finite element problem in the patch subdomain $\omega_{\boldsymbol{a}}$. For Dirichlet boundary vertices $\boldsymbol{a} \in \mathcal{V}_{\mathrm{D}}$, this problem is well-posed with a unique minimizer since the space $\boldsymbol{V}_p(\omega_{\boldsymbol{a}})$ of (2.3) does not impose the normal constraint everywhere on $\partial\omega_{\boldsymbol{a}}$. For interior and Neumann vertices $\boldsymbol{a} \in \mathcal{V}_\Omega \cup \mathcal{V}_{\mathrm{N}}$, the source term in the divergence constraint satisfies the compatibility condition

$$(\Pi_{\mathcal{T}}^p(\psi_{\boldsymbol{a}} \nabla{\cdot}\boldsymbol{v} + \nabla\psi_{\boldsymbol{a}}{\cdot}\boldsymbol{\tau}_{\mathcal{T}}), 1)_{\omega_{\boldsymbol{a}}} = (\nabla{\cdot}\boldsymbol{v}, \psi_{\boldsymbol{a}})_{\omega_{\boldsymbol{a}}} + (\boldsymbol{\tau}_{\mathcal{T}}, \nabla\psi_{\boldsymbol{a}})_{\omega_{\boldsymbol{a}}} = 0,$$

where the second equality follows from Lemma 4.1. Therefore, $\boldsymbol{\sigma}_{\boldsymbol{a}}$ is also well-defined for interior and Neumann vertices $\boldsymbol{a} \in \mathcal{V}_\Omega \cup \mathcal{V}_{\mathrm{N}}$. □

It follows from Lemma 4.2 that $P_{\mathcal{T}}^p(\boldsymbol{v}) \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div}, \Omega)$ is well-defined for every $\boldsymbol{v} \in \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div}, \Omega)$.

4.2 Proof of the commuting property (3.4)

We are now ready to establish:

Lemma 4.3 (Commuting property (3.4))**.** *$P_{\mathcal{T}}^p$ satisfies (3.4).*

Proof. Since the functions $\{\psi_{\boldsymbol{a}}\}_{\boldsymbol{a}\in\mathcal{V}}$ form a partition of unity over Ω, i.e., $\sum_{\boldsymbol{a}\in\mathcal{V}} \psi_{\boldsymbol{a}} = 1$, and consequently $\sum_{\boldsymbol{a}\in\mathcal{V}} \nabla\psi_{\boldsymbol{a}} = \boldsymbol{0}$, we find from (3.3) and (3.2) that

$$\nabla{\cdot}P_{\mathcal{T}}^p(\boldsymbol{v}) = \sum_{\boldsymbol{a}\in\mathcal{V}} \nabla{\cdot}\boldsymbol{\sigma}_{\boldsymbol{a}} = \sum_{\boldsymbol{a}\in\mathcal{V}} \left\{\Pi_{\mathcal{T}}^p(\psi_{\boldsymbol{a}}\nabla{\cdot}\boldsymbol{v} + \nabla\psi_{\boldsymbol{a}}{\cdot}\boldsymbol{\tau}_{\mathcal{T}})\right\} = \Pi_{\mathcal{T}}^p(\nabla{\cdot}\boldsymbol{v}). \tag{4.3}$$

□

4.3 Proof of the approximation property (3.6)

Let us start with two useful technical results. For a given vertex $\boldsymbol{a} \in \mathcal{V}$, let the space $H^1_*(\omega_{\boldsymbol{a}})$ be defined by

$$H^1_*(\omega_{\boldsymbol{a}}) := \begin{cases} \{\varphi \in H^1(\omega_{\boldsymbol{a}}), \quad (\varphi, 1)_{\omega_{\boldsymbol{a}}} = 0\} & \text{if } \boldsymbol{a} \in \mathcal{V}_\Omega \cup \mathcal{V}_{\mathrm{N}}, \\ \{\varphi \in H^1(\omega_{\boldsymbol{a}}), \quad \varphi|_{\partial\omega_{\boldsymbol{a}} \cap \Gamma_{\mathrm{D}}^{\boldsymbol{a}}} = 0\} & \text{if } \boldsymbol{a} \in \mathcal{V}_{\mathrm{D}}, \end{cases} \tag{4.4}$$

where we recall that $\Gamma_{\mathrm{D}}^{\boldsymbol{a}}$ contains those boundary faces from Γ_{D} that share the vertex $\boldsymbol{a}$. Recall also the discrete spaces $\boldsymbol{V}_p(\omega_{\boldsymbol{a}})$ defined in (2.3). The following result has been shown in Braess *et al.* [8, Theorem 7] in two space dimensions and [30, Corollaries 3.3, 3.6, and 3.8] in three space dimensions, crucially building on [16] and [21] to achieve the independence of the involved constant on the polynomial degree p.

Lemma 4.4 (Stability of patchwise flux equilibration)**.** *Let a vertex $\boldsymbol{a} \in \mathcal{V}$ be fixed, and let $g_{\boldsymbol{a}} \in \mathcal{P}_p(\mathcal{T}_{\boldsymbol{a}})$ and $\boldsymbol{\tau}_{\boldsymbol{a}} \in \boldsymbol{RTN}_p(\mathcal{T}_{\boldsymbol{a}})$ be given discontinuous piecewise polynomials with the condition $(g_{\boldsymbol{a}}, 1)_{\omega_{\boldsymbol{a}}} = 0$ if $\boldsymbol{a} \in \mathcal{V}_\Omega \cup \mathcal{V}_{\mathrm{N}}$. Then, there exists a constant C, depending only on the space dimension d and the mesh shape-regularity parameter $\kappa_{\mathcal{T}}$, such that*

$$\min_{\substack{\boldsymbol{v}_{\boldsymbol{a}} \in \boldsymbol{V}_p(\omega_{\boldsymbol{a}}) \\ \nabla\cdot\boldsymbol{v}_{\boldsymbol{a}} = g_{\boldsymbol{a}}}} \|\boldsymbol{v}_{\boldsymbol{a}} - \boldsymbol{\tau}_{\boldsymbol{a}}\|_{\omega_{\boldsymbol{a}}} \le C \sup_{\substack{\varphi \in H^1_*(\omega_{\boldsymbol{a}}) \\ \|\nabla\varphi\|_{\omega_{\boldsymbol{a}}} = 1}} \left\{(g_{\boldsymbol{a}}, \varphi)_{\omega_{\boldsymbol{a}}} + (\boldsymbol{\tau}_{\boldsymbol{a}}, \nabla\varphi)_{\omega_{\boldsymbol{a}}}\right\}.$$

We shall also use the following auxiliary bound for face terms based on the bubble function technique of Verfürth, cf. [46], from a posteriori error analysis.

Lemma 4.5 (Bound on face terms)**.** *Let a mesh face $F \in \mathcal{F}$ be fixed, and let $\mathcal{T}_F$ be the set of one or two mesh elements $K \in \mathcal{T}$ to which F belongs, with ω_F the corresponding open subdomain. Let h_F denote the diameter of F. Then, there exists a constant C, depending only on the space dimension d, the mesh shape-regularity parameter $\kappa_{\mathcal{T}}$, and the polynomial degree p, such that*

$$h_F^{1/2}\|q_h\|_F \le C \sup_{\substack{\varphi \in H^1(\omega_F) \\ \varphi = 0 \text{ on } \partial\omega_F \setminus F \\ \|\nabla\varphi\|_{\omega_F} = 1}} (q_h, \varphi)_F \qquad \forall q_h \in \mathcal{P}_p(F).$$

We are now ready to prove the statement (3.6) from Theorem 3.2, where we now employ the shorthand notation $e_{K,p}(\boldsymbol{v})$ from (3.11). Let $\boldsymbol{v} \in \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ be arbitrary. Since it follows from $\nabla{\cdot}P^p_{\mathcal{T}}(\boldsymbol{v}) = \Pi^p_{\mathcal{T}}(\nabla{\cdot}\boldsymbol{v})$ that

$$\frac{h_K}{p+1}\|\nabla{\cdot}\boldsymbol{v} - \nabla{\cdot}P^p_{\mathcal{T}}(\boldsymbol{v})\|_K \le e_{K,p}(\boldsymbol{v}),$$

it only remains to prove that

$$\|\boldsymbol{v} - P^p_{\mathcal{T}}(\boldsymbol{v})\|_K \le C\left\{\sum_{K'\in\mathcal{T}_K} e_{K',p}(\boldsymbol{v})^2\right\}^{\frac{1}{2}} \qquad \forall K\in\mathcal{T}. \tag{4.5}$$

We proceed for this purpose in two steps.

Step 1. Bound on $\boldsymbol{\sigma_a}$. Recall that $\boldsymbol{\sigma_a}$ is defined in (3.2) with $\boldsymbol{\tau}_{\mathcal{T}}$ defined elementwise in (3.1).

Lemma 4.6 (Bound on $\boldsymbol{\sigma_a}$)**.** *There exists a constant C, depending only on d, $\kappa_{\mathcal{T}}$, and p, such that*

$$\|\boldsymbol{\sigma_a} - \boldsymbol{I}^p_{\mathcal{T}}(\psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}})\|_{\omega_{\boldsymbol{a}}} \le C\left\{\sum_{K\in\mathcal{T}_{\boldsymbol{a}}}[e_{K,p}(\boldsymbol{v})]^2\right\}^{\frac{1}{2}} \qquad \forall \boldsymbol{a}\in\mathcal{V}. \tag{4.6}$$

Proof. First, since $\boldsymbol{I}^p_{\mathcal{T}}(\psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}}) \in \boldsymbol{RTN}_p(\mathcal{T}_{\boldsymbol{a}})$, we can apply Lemma 4.4 to $\boldsymbol{\sigma_a}$, with the choices $\boldsymbol{\tau_a} := \boldsymbol{I}^p_{\mathcal{T}}(\psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}})$ and $g_{\boldsymbol{a}} := \Pi^p_{\mathcal{T}}(\psi_{\boldsymbol{a}}\nabla{\cdot}\boldsymbol{v} + \nabla\psi_{\boldsymbol{a}}{\cdot}\boldsymbol{\tau}_{\mathcal{T}}) \in \mathcal{P}_p(\mathcal{T}_{\boldsymbol{a}})$ to obtain

$$\|\boldsymbol{\sigma_a} - \boldsymbol{I}^p_{\mathcal{T}}(\psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}})\|_{\omega_{\boldsymbol{a}}} \le C \sup_{\substack{\varphi\in H^1_*(\omega_{\boldsymbol{a}})\\ \|\nabla\varphi\|_{\omega_{\boldsymbol{a}}}=1}} \left\{(g_{\boldsymbol{a}},\varphi)_{\omega_{\boldsymbol{a}}} + (\boldsymbol{I}^p_{\mathcal{T}}(\psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}}),\nabla\varphi)_{\omega_{\boldsymbol{a}}}\right\}, \tag{4.7}$$

where the space $H^1_*(\omega_{\boldsymbol{a}})$ is defined in (4.4). Let $h_{\omega_{\boldsymbol{a}}}$ denote the diameter of $\omega_{\boldsymbol{a}}$ and recall the Poincaré inequality $\|v\|_{\omega_{\boldsymbol{a}}} \le Ch_{\omega_{\boldsymbol{a}}}\|\nabla v\|_{\omega_{\boldsymbol{a}}}$ on $H^1_*(\omega_{\boldsymbol{a}})$, with a constant C depending only on the dimension d and on $\kappa_{\mathcal{T}}$. Moreover, note that the shape-regularity of the mesh implies that $h_{\omega_{\boldsymbol{a}}} \approx h_K \approx h_F$ for all $K\in\mathcal{T}_{\boldsymbol{a}}$ and all $F\in\mathcal{F}^{\mathrm{in}}_{\boldsymbol{a}}$.

Define for any $\boldsymbol{\varsigma}_{\mathcal{T}} \in \boldsymbol{C}^1(\mathcal{T})$ the jump $[\![\boldsymbol{\varsigma}_{\mathcal{T}}]\!]$ on an interior face F shared by two mesh elements K_+ and K_- by $[\![\boldsymbol{\varsigma}_{\mathcal{T}}]\!] := (\boldsymbol{\varsigma}_{\mathcal{T}}|_{K_+})|_F - (\boldsymbol{\varsigma}_{\mathcal{T}}|_{K_-})|_F$; here $\boldsymbol{n}_F := \boldsymbol{n}_{K_-} = -\boldsymbol{n}_{K_+}$ is the unit normal to F that points outward K_- and inward K_+. Similarly, if F is a boundary face, then we define $[\![\boldsymbol{\varsigma}_{\mathcal{T}}]\!] := \boldsymbol{\varsigma}_{\mathcal{T}}|_F$. To bound the right-hand side of (4.7), consider an arbitrary $\varphi\in H^1_*(\omega_{\boldsymbol{a}})$ such that $\|\nabla\varphi\|_{\omega_{\boldsymbol{a}}} = 1$. Then, using integration by parts elementwise, we find that

$$\begin{aligned}\left(\boldsymbol{I}^p_{\mathcal{T}}(\psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}}),\nabla\varphi\right)_{\omega_{\boldsymbol{a}}} &= \sum_{F\in\mathcal{F}^{\mathrm{in}}_{\boldsymbol{a}}}\left([\![\boldsymbol{I}^p_{\mathcal{T}}(\psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}})]\!]{\cdot}\boldsymbol{n}_F,\varphi\right)_F - \sum_{K\in\mathcal{T}_{\boldsymbol{a}}}\left(\nabla{\cdot}\boldsymbol{I}^p_{\mathcal{T}}(\psi_a\boldsymbol{\tau}_{\mathcal{T}}),\varphi\right)_K \\ &= \sum_{F\in\mathcal{F}^{\mathrm{in}}_{\boldsymbol{a}}}\left(\Pi^p_F(\psi_{\boldsymbol{a}}[\![\boldsymbol{\tau}_{\mathcal{T}}]\!]{\cdot}\boldsymbol{n}_F),\varphi\right)_F - \left(\Pi^p_{\mathcal{T}}(\nabla_{\mathcal{T}}{\cdot}(\psi_a\boldsymbol{\tau}_{\mathcal{T}})),\varphi\right)_{\omega_{\boldsymbol{a}}}.\end{aligned}$$

Here, in the first identity, the set of faces can be restricted to $\mathcal{F}^{\mathrm{in}}_{\boldsymbol{a}}$; indeed, for interior vertices, this follows from the fact that $\psi_{\boldsymbol{a}}$ vanishes on $\partial\omega_{\boldsymbol{a}}$, whereas for boundary vertices, $\varphi\in H^1_*(\omega_{\boldsymbol{a}})$ vanishes on $\Gamma^{\boldsymbol{a}}_{\mathrm{D}}$. The second identity is then obtained from the definition of the elementwise canonical interpolant $\boldsymbol{I}^p_{\mathcal{T}}$ in (2.1) and the commutation identity (2.2). Expanding $\nabla_{\mathcal{T}}{\cdot}(\psi_a\boldsymbol{\tau}_{\mathcal{T}}) = \nabla\psi_{\boldsymbol{a}}{\cdot}\boldsymbol{\tau}_{\mathcal{T}} + \psi_{\boldsymbol{a}}\nabla_{\mathcal{T}}{\cdot}\boldsymbol{\tau}_{\mathcal{T}}$ and simplifying gives

$$\begin{aligned}(g_{\boldsymbol{a}},\varphi)_{\omega_{\boldsymbol{a}}} + (\boldsymbol{I}^p_{\mathcal{T}}(\psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}}),\nabla\varphi)_{\omega_{\boldsymbol{a}}} &= (\Pi^p_{\mathcal{T}}(\psi_{\boldsymbol{a}}\nabla_{\mathcal{T}}{\cdot}(\boldsymbol{v}-\boldsymbol{\tau}_{\mathcal{T}})),\varphi)_{\omega_{\boldsymbol{a}}} \\ &\quad + \sum_{F\in\mathcal{F}^{\mathrm{in}}_{\boldsymbol{a}}}\left(\Pi^p_F(\psi_{\boldsymbol{a}}[\![\boldsymbol{\tau}_{\mathcal{T}}]\!]{\cdot}\boldsymbol{n}_F),\varphi\right)_F.\end{aligned} \tag{4.8}$$

We now bound the two terms on the right-hand side of (4.8) separately.

To bound the first term, we consider first the case $p\ge 1$: using the divergence constraint on $\boldsymbol{\tau}_{\mathcal{T}}$ in (3.1), the orthogonality of the L^2-projections, the approximation bound $\|\varphi - \Pi^{p-1}_{\mathcal{T}}\varphi\|_K \le C\frac{h_K}{p+1}\|\nabla\varphi\|_K$ (note that $\frac{1}{p}\le\frac{2}{p+1}$ for all $p\ge 1$), along with $\|\psi_{\boldsymbol{a}}\|_{\infty,\omega_{\boldsymbol{a}}} = 1$ and $\|\nabla\varphi\|_{\omega_{\boldsymbol{a}}} = 1$, we find that there is a constant

C, depending only on d and $\kappa_{\mathcal{T}}$, such that

$$(\Pi_{\mathcal{T}}^{p}(\psi_{\boldsymbol{a}}\nabla_{\mathcal{T}}\cdot(\boldsymbol{v}-\boldsymbol{\tau}_{\mathcal{T}})),\varphi)_{\omega_{\boldsymbol{a}}} = \left(\nabla\cdot\boldsymbol{v}-\Pi_{\mathcal{T}}^{p}(\nabla\cdot\boldsymbol{v}),\psi_{\boldsymbol{a}}\Pi_{\mathcal{T}}^{p}(\varphi-\Pi_{\mathcal{T}}^{p-1}\varphi)\right)_{\omega_{\boldsymbol{a}}}$$
$$\leq C\left\{\sum_{K\in\mathcal{T}_{\boldsymbol{a}}}\frac{h_K^2}{(p+1)^2}\|\nabla\cdot\boldsymbol{v}-\Pi_{\mathcal{T}}^{p}(\nabla\cdot\boldsymbol{v})\|_K^2\right\}^{\frac{1}{2}}$$
$$\leq C\left\{\sum_{K\in\mathcal{T}_{\boldsymbol{a}}}[e_{K,p}(\boldsymbol{v})]^2\right\}^{\frac{1}{2}}.$$

For $p=0$, we instead apply the Cauchy–Schwarz inequality, the stability of the L^2-projection, the Poincaré inequality on $H^1_*(\omega_{\boldsymbol{a}})$, and $\|\nabla\varphi\|_{\omega_{\boldsymbol{a}}}=1$ to get

$$|(\Pi_{\mathcal{T}}^{p}(\psi_{\boldsymbol{a}}\nabla_{\mathcal{T}}\cdot(\boldsymbol{v}-\boldsymbol{\tau}_{\mathcal{T}})),\varphi)_{\omega_{\boldsymbol{a}}}| \leq C\|\nabla_{\mathcal{T}}\cdot(\boldsymbol{v}-\boldsymbol{\tau}_{\mathcal{T}})\|_{\omega_{\boldsymbol{a}}}h_{\omega_{\boldsymbol{a}}}\|\nabla\varphi\|_{\omega_{\boldsymbol{a}}}$$
$$\leq C\left\{\sum_{K\in\mathcal{T}_{\boldsymbol{a}}}[e_{K,p}(\boldsymbol{v})]^2\right\}^{\frac{1}{2}},$$

where C depends only on d and $\kappa_{\mathcal{T}}$.

To bound the second term on the right-hand side of (4.8), we recall the trace inequality

$$\|\varphi\|_F^2 \leq C\left(\|\nabla\varphi\|_K\|\varphi\|_K + h_K^{-1}\|\varphi\|_K^2\right),$$

for any $\varphi\in H^1(K)$ and $F\in\mathcal{F}_K$, where C depends only on d and $\kappa_{\mathcal{T}}$. Combined with the Poincaré inequality on $H^1_*(\omega_{\boldsymbol{a}})$ and $\|\nabla\varphi\|_{\omega_{\boldsymbol{a}}}=1$, this gives

$$\sum_{F\in\mathcal{F}_{\boldsymbol{a}}^{\text{in}}}\left|\left(\Pi_F^p(\psi_{\boldsymbol{a}}[\![\boldsymbol{\tau}_{\mathcal{T}}]\!]\cdot\boldsymbol{n}_F),\varphi\right)_F\right| \leq C\left\{\sum_{F\in\mathcal{F}_{\boldsymbol{a}}^{\text{in}}}h_F\|[\![\boldsymbol{\tau}_{\mathcal{T}}]\!]\cdot\boldsymbol{n}_F\|_F^2\right\}^{\frac{1}{2}},$$

with C depending only on d and $\kappa_{\mathcal{T}}$. Finally, we invoke Lemma 4.5, yielding, for each $F\in\mathcal{F}_{\boldsymbol{a}}^{\text{in}}$,

$$h_F^{1/2}\|[\![\boldsymbol{\tau}_{\mathcal{T}}]\!]\cdot\boldsymbol{n}_F\|_F \leq C\sup_{\substack{w\in H^1(\omega_F)\\ w=0\text{ on }\partial\omega_F\setminus F\\ \|\nabla w\|_{\omega_F}=1}}([\![\boldsymbol{\tau}_{\mathcal{T}}]\!]\cdot\boldsymbol{n}_F,w)_F, \tag{4.9}$$

where now the constant C depends on the polynomial degree p in addition to d and $\kappa_{\mathcal{T}}$. Fix $w\in H^1(\omega_F)$ such that $w=0$ on $\partial\omega_F\setminus F$ and $\|\nabla w\|_{\omega_F}=1$. By definition, $F\in\mathcal{F}_{\boldsymbol{a}}^{\text{in}}$ means that F is either an internal face shared by two simplices, or a Neumann boundary face. Then, the zero extension of w to Ω belongs to $H^1_{\Gamma_{\mathrm{D}}}(\Omega)$. Since $\boldsymbol{v}\in\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$, we infer from the definition of the weak divergence that

$$(\nabla\cdot\boldsymbol{v},w)_{\omega_F}+(\boldsymbol{v},\nabla w)_{\omega_F}=0.$$

Consequently, developing $([\![\boldsymbol{\tau}_{\mathcal{T}}]\!]\cdot\boldsymbol{n}_F,w)_F$ shows that

$$|([\![\boldsymbol{\tau}_{\mathcal{T}}]\!]\cdot\boldsymbol{n}_F,w)_F| = |(\nabla_{\mathcal{T}}\cdot\boldsymbol{\tau}_{\mathcal{T}},w)_{\omega_F}+(\boldsymbol{\tau}_{\mathcal{T}},\nabla w)_{\omega_F}|$$
$$\leq |(\nabla_{\mathcal{T}}\cdot(\boldsymbol{\tau}_{\mathcal{T}}-\boldsymbol{v}),w-\Pi_{\mathcal{T}}^{p}w)_{\omega_F}|+|(\boldsymbol{\tau}_{\mathcal{T}}-\boldsymbol{v},\nabla w)_{\omega_F}|$$
$$\leq \|\nabla_{\mathcal{T}}\cdot(\boldsymbol{\tau}_{\mathcal{T}}-\boldsymbol{v})\|_{\omega_F}\|w-\Pi_{\mathcal{T}}^{p}w\|_{\omega_F}+\|\boldsymbol{\tau}_{\mathcal{T}}-\boldsymbol{v}\|_{\omega_F}\|\nabla w\|_{\omega_F}$$
$$\leq C\sum_{K\in\mathcal{T}_F}\left\{\|\boldsymbol{v}-\boldsymbol{\tau}_{\mathcal{T}}\|_K^2+\frac{h_K^2}{(p+1)^2}\|\nabla\cdot(\boldsymbol{v}-\boldsymbol{\tau}_{\mathcal{T}})\|_K^2\right\}^{1/2},$$

owing to the Cauchy–Schwarz inequality, the orthogonality of the L^2-projection, and the approximation bound $\|w-\Pi_{\mathcal{T}}^{p}w\|_K\leq C\frac{h_K}{p+1}\|\nabla w\|_K$. Hence, Lemma A.1 below implies that

$$\sum_{F\in\mathcal{F}_{\boldsymbol{a}}^{\text{in}}}\left(\Pi_F^p(\psi_{\boldsymbol{a}}[\![\boldsymbol{\tau}_{\mathcal{T}}]\!]\cdot\boldsymbol{n}_F),\varphi\right)_F \leq C\left\{\sum_{K\in\mathcal{T}_{\boldsymbol{a}}}[e_{K,p}(\boldsymbol{v})]^2\right\}^{\frac{1}{2}},$$

where the constant C depends only on d, $\kappa_{\mathcal{T}}$, and the polynomial degree p via (4.9). Combining these bounds implies (4.6). $\square$

Step 2. Bound on $\|\boldsymbol{v} - P_{\mathcal{T}}^p(\boldsymbol{v})\|_K$. Let $K \in \mathcal{T}$. In this second and last step, we first show that

$$\|P_{\mathcal{T}}^p(\boldsymbol{v}) - \boldsymbol{\tau}_{\mathcal{T}}\|_K \le C \left\{ \sum_{K' \in \mathcal{T}_K} [e_{K',p}(\boldsymbol{v})]^2 \right\}^{\frac{1}{2}}. \tag{4.10}$$

Recalling that $\mathcal{V}_K$ denotes the set of vertices of the element K, using the partition of unity $\sum_{\boldsymbol{a} \in \mathcal{V}_K} \psi_{\boldsymbol{a}}|_K = 1$ and the linearity of the elementwise canonical interpolant $\boldsymbol{I}_{\mathcal{T}}^p$ (2.1) as well as definition (3.3) of $P_{\mathcal{T}}^p(\boldsymbol{v})$ and the fact that $\boldsymbol{\tau}_{\mathcal{T}} = \boldsymbol{I}_{\mathcal{T}}^p(\boldsymbol{\tau}_{\mathcal{T}})$, we find that

$$(P_{\mathcal{T}}^p(\boldsymbol{v}) - \boldsymbol{\tau}_{\mathcal{T}})\,|_K = (P_{\mathcal{T}}^p(\boldsymbol{v}) - \boldsymbol{I}_{\mathcal{T}}^p(\boldsymbol{\tau}_{\mathcal{T}}))\,|_K = \sum_{\boldsymbol{a} \in \mathcal{V}_K} (\boldsymbol{\sigma}_{\boldsymbol{a}} - \boldsymbol{I}_{\mathcal{T}}^p(\psi_{\boldsymbol{a}} \boldsymbol{\tau}_{\mathcal{T}}))\,|_K.$$

Thus,

$$\|P_{\mathcal{T}}^p(\boldsymbol{v}) - \boldsymbol{\tau}_{\mathcal{T}}\|_K^2 = \left\| \sum_{\boldsymbol{a} \in \mathcal{V}_K} (\boldsymbol{\sigma}_{\boldsymbol{a}} - \boldsymbol{I}_{\mathcal{T}}^p(\psi_{\boldsymbol{a}} \boldsymbol{\tau}_{\mathcal{T}})) \right\|_K^2 \le (d+1) \sum_{\boldsymbol{a} \in \mathcal{V}_K} \|\boldsymbol{\sigma}_{\boldsymbol{a}} - \boldsymbol{I}_{\mathcal{T}}^p(\psi_{\boldsymbol{a}} \boldsymbol{\tau}_{\mathcal{T}})\|_{\omega_{\boldsymbol{a}}}^2,$$

and Lemma 4.6 then yields (4.10).

Finally, having obtained (4.10), the main bound (4.5) then follows from the triangle inequality and Lemma A.1, since

$$\|\boldsymbol{v} - P_{\mathcal{T}}^p(\boldsymbol{v})\|_K \le \|\boldsymbol{v} - \boldsymbol{\tau}_{\mathcal{T}}\|_K + \|\boldsymbol{\tau}_{\mathcal{T}} - P_{\mathcal{T}}^p(\boldsymbol{v})\|_K \le C \left\{ \sum_{K' \in \mathcal{T}_K} [e_{K',p}(\boldsymbol{v})]^2 \right\}^{\frac{1}{2}}.$$

This completes the proof of the approximation property (3.6) from Theorem 3.2.

4.4 Proof of the projection property (3.5), $\boldsymbol{L}^2$ stability (3.7), and $\boldsymbol{H}(\mathrm{div})$ stability (3.8)

To prove (3.5), we observe that if $\boldsymbol{v} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div}, \Omega)$, then it follows from the definition (3.11) that $e_{K,p}(\boldsymbol{v}) = 0$ for all $K \in \mathcal{T}$, and thus (3.5) follows immediately from (3.6).

To prove (3.7), we observe that, for any $K \in \mathcal{T}$, the triangle inequality yields

$$\|P_{\mathcal{T}}^p(\boldsymbol{v})\|_K \le \|\boldsymbol{v}\|_K + \|\boldsymbol{v} - P_{\mathcal{T}}^p(\boldsymbol{v})\|_K.$$

The first term is trivially contained in the right-hand side of (3.7). Bounding the second one by (3.6), the definition (3.11) of $e_{K,p}(\boldsymbol{v})$ implies that

$$e_{K,p}(\boldsymbol{v}) \le \|\boldsymbol{v}\|_K + \frac{h_K}{(p+1)} \|\nabla \cdot \boldsymbol{v} - \Pi_{\mathcal{T}}^p(\nabla \cdot \boldsymbol{v})\|_K.$$

This shows that (3.7) holds true.

Finally, from (3.7), the bound in (3.8) follows immediately since $\frac{h_K}{p+1} \le h_\Omega$ and since both terms $\|\Pi_{\mathcal{T}}^p(\nabla \cdot \boldsymbol{v})\|_K$ and $\|\nabla \cdot \boldsymbol{v} - \Pi_{\mathcal{T}}^p(\nabla \cdot \boldsymbol{v})\|_K$ are bounded by $\|\nabla \cdot \boldsymbol{v}\|_K$.

5 Proof of Theorem 3.6 (hp-optimal approximation estimates under minimal $\boldsymbol{H}^s(K)$-regularity)

We present here a proof of Theorem 3.6. First, in Section 5.1, we derive an unbalanced but polynomial-degree-robust bound in Proposition 5.1. Then, in Section 5.2, we combine it with Theorem 3.3.

5.1 Polynomial-degree-robust one-sided bound

We present here an auxiliary result which gives a bound where the global-best approximation error (3.10) is bounded in terms of the sums of local-best approximation errors (3.11) with a constant that is *robust with respect to the polynomial degree*, but where the polynomial degree in the local approximation errors is $(p-1)$ instead of p. As a result, in contrast to Theorem 3.3, this is a one-sided inequality and not an equivalence, and it is valid only for $p \ge 1$ and not for $p \ge 0$.

Proposition 5.1 (Polynomial-degree-robust bound)**.** *There exists a constant C, depending only on the space dimension d and the shape-regularity parameter $\kappa_{\mathcal{T}}$ of $\mathcal{T}$, such that, for any $\boldsymbol{v} \in \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div}, \Omega)$ and any $p \geq 1$,*

$$[E_{\mathcal{T},p}(\boldsymbol{v})]^2 \leq C \sum_{K \in \mathcal{T}} [e_{K,p-1}(\boldsymbol{v})]^2. \tag{5.1}$$

Let us stress that (5.1) is similar to the first inequality in (3.12) but the constant C above is independent of the polynomial degree p.

The rest of this section is devoted to the proof of Proposition 5.1, performed in the spirit of that of Theorem 3.3. We start by adapting Definition 3.1 as follows.

Definition 5.2 (Alternative locally-defined mapping from $\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div}, \Omega)$ to $\boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div}, \Omega)$)**.** *Let $\boldsymbol{v} \in \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div}, \Omega)$ be arbitrary. Let $\boldsymbol{\tau}_{\mathcal{T}}$ be defined elementwise by*

$$\boldsymbol{\tau}_{\mathcal{T}}|_K := \underset{\substack{\boldsymbol{\varsigma}_K \in \boldsymbol{RTN}_{p-1}(K) \\ \nabla\cdot\boldsymbol{\varsigma}_K = \Pi_{\mathcal{T}}^{p-1}(\nabla\cdot\boldsymbol{v})}}{\arg\min} \|\boldsymbol{v} - \boldsymbol{\varsigma}_K\|_K \qquad \forall K \in \mathcal{T}. \tag{5.2}$$

For each mesh vertex $\boldsymbol{a} \in \mathcal{V}$, the patchwise contributions $\boldsymbol{\sigma}_{\boldsymbol{a}}$ are now defined as

$$\boldsymbol{\sigma}_{\boldsymbol{a}} := \underset{\substack{\boldsymbol{\varsigma}_{\boldsymbol{a}} \in \boldsymbol{V}_p(\omega_{\boldsymbol{a}}) \\ \nabla\cdot\boldsymbol{\varsigma}_{\boldsymbol{a}} = \Pi_{\mathcal{T}}^p(\psi_{\boldsymbol{a}}\nabla\cdot\boldsymbol{v}) + \nabla\psi_{\boldsymbol{a}}\cdot\boldsymbol{\tau}_{\mathcal{T}}}}{\arg\min} \|\boldsymbol{\varsigma}_{\boldsymbol{a}} - \psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}}\|_{\omega_{\boldsymbol{a}}}, \tag{5.3}$$

with the spaces $\boldsymbol{V}_p(\omega_{\boldsymbol{a}})$ still defined in (2.3). Finally, after extending each $\boldsymbol{\sigma}_{\boldsymbol{a}}$ from $\omega_{\boldsymbol{a}}$ to the rest of Ω by zero, the equilibrated flux reconstruction $\boldsymbol{\sigma}_{\mathcal{T}} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div}, \Omega)$ is defined as

$$\boldsymbol{\sigma}_{\mathcal{T}} := \sum_{\boldsymbol{a} \in \mathcal{V}} \boldsymbol{\sigma}_{\boldsymbol{a}}. \tag{5.4}$$

The prescription (5.2) is similar to (3.1) up to the employment of the polynomial degree $p-1$ in place of p. Likewise, (5.3) is similar to (3.2), up to two subtle differences: the canonical interpolant $\boldsymbol{I}_{\mathcal{T}}^p$ is no longer used (since from (5.2), $\psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}}$ already lies in $\boldsymbol{RTN}_p(\mathcal{T})$), and the projection $\Pi_{\mathcal{T}}^p$ in the divergence constraint only concerns the term $\psi_{\boldsymbol{a}}\nabla\cdot\boldsymbol{v}$. Definition 5.2 is also well posed. In particular, existence and uniqueness for the local minimization problems (5.3) follows as in Lemma 4.2, since the orthogonality property (4.2) also holds here, implying that (4.1) is satisfied with the above definitions. Also, just as in (4.3), we deduce that

$$\nabla\cdot\boldsymbol{\sigma}_{\mathcal{T}} = \Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{v}).$$

We continue with the following lemma.

Lemma 5.3 (Bound on $\boldsymbol{\sigma}_{\boldsymbol{a}}$)**.** *Let $\boldsymbol{\tau}_{\mathcal{T}}$ be given by (5.2) and let $\boldsymbol{\sigma}_{\boldsymbol{a}}$ be given by (5.3). Then, there exists a constant C, depending only on d and $\kappa_{\mathcal{T}}$, such that*

$$\|\boldsymbol{\sigma}_{\boldsymbol{a}} - \psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}}\|_{\omega_{\boldsymbol{a}}} \leq C \left\{ \sum_{K \in \mathcal{T}_{\boldsymbol{a}}} [e_{K,p-1}(\boldsymbol{v})]^2 \right\}^{\frac{1}{2}} \qquad \forall \boldsymbol{a} \in \mathcal{V}. \tag{5.5}$$

Proof. Fix a vertex $\boldsymbol{a} \in \mathcal{V}$. We rely on Lemma 4.4, where we take $\boldsymbol{\tau}_{\boldsymbol{a}} := \psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}}$ and $g_{\boldsymbol{a}} := \Pi_{\mathcal{T}}^p(\psi_{\boldsymbol{a}}\nabla\cdot\boldsymbol{v}) + \nabla\psi_{\boldsymbol{a}}\cdot\boldsymbol{\tau}_{\mathcal{T}}$ in order to apply it to our construction (5.3) from Definition 5.2. This yields

$$\|\boldsymbol{\sigma}_{\boldsymbol{a}} - \psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}}\|_{\omega_{\boldsymbol{a}}} \leq C \sup_{\substack{v \in H_*^1(\omega_{\boldsymbol{a}}) \\ \|\nabla\varphi\|_{\omega_{\boldsymbol{a}}} = 1}} \left\{ (g_{\boldsymbol{a}}, \varphi)_{\omega_{\boldsymbol{a}}} + (\boldsymbol{\tau}_{\boldsymbol{a}}, \nabla\varphi)_{\omega_{\boldsymbol{a}}} \right\},$$

where the involved constant C is crucially independent of the polynomial degree p. Let $\varphi \in H_*^1(\omega_{\boldsymbol{a}})$ with $\|\nabla\varphi\|_{\omega_{\boldsymbol{a}}} = 1$ be fixed, where we recall that the space $H_*^1(\omega_{\boldsymbol{a}})$ is defined in (4.4). Then, the product $\psi_{\boldsymbol{a}}\varphi \in H_{\Gamma_{\mathrm{D}}}^1(\Omega)$ for any $\boldsymbol{a} \in \mathcal{V}$ and thus the definition of the weak divergence implies that

$$\big(\boldsymbol{v}, \nabla(\psi_{\boldsymbol{a}}\varphi)\big)_{\omega_{\boldsymbol{a}}} + \big(\nabla\cdot\boldsymbol{v}, \psi_{\boldsymbol{a}}\varphi\big)_{\omega_{\boldsymbol{a}}} = 0.$$

Then, the product rule and the orthogonality of the L^2-projection give

$$\begin{aligned}
(g_{\boldsymbol{a}}, \varphi)_{\omega_{\boldsymbol{a}}} + (\boldsymbol{\tau}_{\boldsymbol{a}}, \nabla\varphi)_{\omega_{\boldsymbol{a}}} &= \big(\Pi_{\mathcal{T}}^p(\psi_a\nabla\cdot\boldsymbol{v}), \varphi\big)_{\omega_{\boldsymbol{a}}} + (\nabla\psi_{\boldsymbol{a}}\cdot\boldsymbol{\tau}_{\mathcal{T}}, \varphi)_{\omega_{\boldsymbol{a}}} + \big(\psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}}, \nabla\varphi\big)_{\omega_{\boldsymbol{a}}} \\
&= \big(\nabla\cdot\boldsymbol{v}, \psi_{\boldsymbol{a}}\Pi_{\mathcal{T}}^p(\varphi)\big)_{\omega_{\boldsymbol{a}}} + \big(\boldsymbol{\tau}_{\mathcal{T}}, \nabla(\psi_{\boldsymbol{a}}\varphi)\big)_{\omega_{\boldsymbol{a}}} \\
&= \big(\nabla\cdot\boldsymbol{v}, \psi_{\boldsymbol{a}}(\Pi_{\mathcal{T}}^p(\varphi) - \varphi)\big)_{\omega_{\boldsymbol{a}}} + \big(\boldsymbol{\tau}_{\mathcal{T}} - \boldsymbol{v}, \nabla(\psi_{\boldsymbol{a}}\varphi)\big)_{\omega_{\boldsymbol{a}}} \\
&= \big(\psi_{\boldsymbol{a}}(\nabla\cdot\boldsymbol{v} - \Pi_{\mathcal{T}}^{p-1}(\nabla\cdot\boldsymbol{v})), \Pi_{\mathcal{T}}^p(\varphi) - \varphi\big)_{\omega_{\boldsymbol{a}}} + \big(\boldsymbol{\tau}_{\mathcal{T}} - \boldsymbol{v}, \nabla(\psi_{\boldsymbol{a}}\varphi)\big)_{\omega_{\boldsymbol{a}}},
\end{aligned}$$

since $\psi_{\boldsymbol{a}}\Pi_{\mathcal{T}}^{p-1}(\nabla{\cdot}\boldsymbol{v})$ is a piecewise polynomial of degree at most p. Therefore, we have

$$\begin{aligned}|(g_{\boldsymbol{a}},\varphi)_{\omega_{\boldsymbol{a}}}+(\boldsymbol{\tau}_{\boldsymbol{a}},\nabla\varphi)_{\omega_{\boldsymbol{a}}}| &\leq C\sum_{K\in\mathcal{T}_{\boldsymbol{a}}}\left[\frac{h_K}{p}\|\nabla{\cdot}\boldsymbol{v}-\Pi_{\mathcal{T}}^{p-1}(\nabla{\cdot}\boldsymbol{v})\|_K\right]\|\nabla\varphi\|_{\omega_{\boldsymbol{a}}}\\ &\qquad+\|\boldsymbol{v}-\boldsymbol{\tau}_{\mathcal{T}}\|_{\omega_{\boldsymbol{a}}}\|\nabla(\psi_{\boldsymbol{a}}\varphi)\|_{\omega_{\boldsymbol{a}}}\\ &\leq C\left(1+\|\nabla(\psi_{\boldsymbol{a}}\varphi)\|_{\omega_{\boldsymbol{a}}}\right)\left\{\sum_{K\in\mathcal{T}_{\boldsymbol{a}}}[e_{K,p-1}(\boldsymbol{v})]^2\right\}^{\frac{1}{2}},\end{aligned}$$

where we have used $\|\psi_{\boldsymbol{a}}\|_{\infty,\omega_{\boldsymbol{a}}}=1$, the hp approximation bound $\|\varphi-\Pi_{\mathcal{T}}^{p}(\varphi)\|_K\leq C\frac{h_K}{p+1}\|\nabla\varphi\|_K\leq C\frac{h_K}{p}\|\nabla\varphi\|_K$, the Cauchy–Schwarz inequality, the scaling $\|\nabla\varphi\|_{\omega_{\boldsymbol{a}}}=1$, and Lemma A.1 below applied with $(p-1)$ in place of p. Finally, the bound (5.5) follows from the inequality $\|\nabla(\psi_{\boldsymbol{a}}\varphi)\|_{\omega_{\boldsymbol{a}}}\leq C\|\nabla\varphi\|_{\omega_{\boldsymbol{a}}}\leq C$ for all $\varphi\in H^1_*(\omega_{\boldsymbol{a}})$, owing to the Poincaré inequality on $H^1_*(\omega_{\boldsymbol{a}})$ and $\|\nabla\varphi\|_{\omega_{\boldsymbol{a}}}=1$. □

We are now ready to complete the proof of Proposition 5.1. Let $\boldsymbol{v}\in\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ and let $\boldsymbol{\sigma}_{\mathcal{T}}$ be given by Definition 5.2. The triangle inequality gives

$$\|\boldsymbol{v}-\boldsymbol{\sigma}_{\mathcal{T}}\|\leq\|\boldsymbol{v}-\boldsymbol{\tau}_{\mathcal{T}}\|+\|\boldsymbol{\tau}_{\mathcal{T}}-\boldsymbol{\sigma}_{\mathcal{T}}\|,$$

and Lemma A.1 below applied with $(p-1)$ in place of p allows to bound the divergence-constrained minimization in (5.2) as

$$\|\boldsymbol{v}-\boldsymbol{\tau}_{\mathcal{T}}\|\leq C\left\{\sum_{K\in\mathcal{T}}[e_{K,p-1}(\boldsymbol{v})]^2\right\}^{\frac{1}{2}},$$

where C only depends on d and $\kappa_{\mathcal{T}}$. Finally, we obtain (5.1) from the estimate

$$\|\boldsymbol{\sigma}_{\mathcal{T}}-\boldsymbol{\tau}_{\mathcal{T}}\|^2=\sum_{K\in\mathcal{T}}\left\|\sum_{\boldsymbol{a}\in\mathcal{V}_K}(\boldsymbol{\sigma}_{\boldsymbol{a}}-\psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}})\right\|_K^2\leq(d+1)\sum_{\boldsymbol{a}\in\mathcal{V}}\|\boldsymbol{\sigma}_{\boldsymbol{a}}-\psi_{\boldsymbol{a}}\boldsymbol{\tau}_{\mathcal{T}}\|_{\omega_{\boldsymbol{a}}}^2,$$

Lemma 5.3, and picking $\boldsymbol{\sigma}_{\mathcal{T}}$ in (3.10).

5.2 Proof of Theorem 3.6

The proof of Theorem 3.6 hinges on the bounds from Theorem 3.3 and Proposition 5.1. Recall the definitions (3.10) of $E_{\mathcal{T},p}(\boldsymbol{v})$ and (3.11) of $e_{K,p}(\boldsymbol{v})$. Recall also the notation $\delta_{s<1}:=1$ if $s<1$ and $\delta_{s<1}:=0$ if $s\geq1$. We proceed in two steps.

Step 1. Case $p\leq s$. We first suppose that $p\leq s$ and let $t:=\min(s,p+1)$. Here, we will employ Theorem 3.3. Since $\mathcal{P}_p(K;\mathbb{R}^d)\subset\boldsymbol{RTN}_p(K)$, well-known hp-approximation bounds, see e.g. [2, Lemma 4.1], imply that

$$[e_{K,p}(\boldsymbol{v})]^2\leq C\left\{\left[\frac{h_K^t}{(p+1)^s}\|v\|_{\boldsymbol{H}^s(K)}\right]^2+\delta_{s<1}\left[\frac{h_K}{p+1}\|\nabla{\cdot}\boldsymbol{v}\|_K\right]^2\right\},\tag{5.6}$$

for each $K\in\mathcal{T}$, with C depending only on s, d, $\kappa_{\mathcal{T}}$. Note that for $s<1$, we applied here the trivial bound $\|\nabla{\cdot}\boldsymbol{v}-\Pi_{\mathcal{T}}^{p}(\nabla{\cdot}\boldsymbol{v})\|_K\leq\|\nabla{\cdot}\boldsymbol{v}\|_K$ as $\boldsymbol{v}|_K\in\boldsymbol{H}^s(K)$ is insufficient to improve the bound on the error of the divergence. Combining (5.6) with the first bound in (3.12) of Theorem 3.3 then implies that there exists a constant $C_{s,d,\kappa_{\mathcal{T}},p}$ depending only on s, d, $\kappa_{\mathcal{T}}$, and p, such that

$$[E_{\mathcal{T},p}(\boldsymbol{v})]^2\leq C_{s,d,\kappa_{\mathcal{T}},p}\sum_{K\in\mathcal{T}}\left\{\left[\frac{h_K^t}{(p+1)^s}\|v\|_{\boldsymbol{H}^s(K)}\right]^2+\delta_{s<1}\left[\frac{h_K}{p+1}\|\nabla{\cdot}\boldsymbol{v}\|_K\right]^2\right\}.$$

Define then the constant $C^\star_{s,d,\kappa_{\mathcal{T}}}:=\max_{0\leq p\leq s}C_{s,d,\kappa_{\mathcal{T}},p}$, so that, for all $p\leq s$,

$$[E_{\mathcal{T},p}(\boldsymbol{v})]^2\leq C^\star_{s,d,\kappa_{\mathcal{T}}}\sum_{K\in\mathcal{T}}\left\{\left[\frac{h_K^t}{(p+1)^s}\|v\|_{\boldsymbol{H}^s(K)}\right]^2+\delta_{s<1}\left[\frac{h_K}{p+1}\|\nabla{\cdot}\boldsymbol{v}\|_K\right]^2\right\}.$$

This implies (3.13) for any $p\leq s$ with constant $C=C^\star_{s,d,\kappa_{\mathcal{T}}}$.

Step 2. Case $p > s$. Now consider the case $p > s$; since p is an integer, this implies that $p \geq 1$. Here we rely on Proposition 5.1. The approximation bounds, similarly to (5.6), imply that there exists a constant C, depending only on s, d, and $\kappa_{\mathcal{T}}$, such that

$$[e_{K,p-1}(\boldsymbol{v})]^2 \leq C\left\{\left[\frac{h_K^s}{p^s}\|\boldsymbol{v}\|_{\boldsymbol{H}^s(K)}\right]^2 + \delta_{s<1}\left[\frac{h_K}{p}\|\nabla\cdot\boldsymbol{v}\|_K\right]^2\right\},$$

for all $K \in \mathcal{T}$. Note that $p+1 \leq 2p$ for all $p \geq 1$, so that the terms p^s in the denominators above can be replaced by $(p+1)^s$ at the cost of an extra s-dependent constant, and similarly for $1/p \leq 2/(p+1)$. Hence, the inequality (5.1) of Proposition 5.1 and summation over the elements of $\mathcal{T}$ shows that there exists a constant $C^{\sharp}_{s,d,\kappa_{\mathcal{T}}}$ depending only on s, d, and $\kappa_{\mathcal{T}}$ such that (3.13) holds with constant $C = C^{\sharp}_{s,d,\kappa_{\mathcal{T}}}$ for all $p > s$.

Conclusion. Combining Steps 1 and 2 shows that (3.13) holds for general $s \geq 0$ and $p \geq 0$ with a constant C that can be taken as $\max\{C^{\star}_{s,d,\kappa_{\mathcal{T}}}, C^{\sharp}_{s,d,\kappa_{\mathcal{T}}}\}$, which then depends only on s, d, and $\kappa_{\mathcal{T}}$.

Remark 5.4 (Full hp-optimality)**.** Theorem 3.6 shows that optimal order convergence rates with respect to both the mesh-sizes h_K and the polynomial degree p can be obtained despite the unfavorable dependence of the constant C on the polynomial degree p in Theorem 3.3 and unbalanced polynomial degrees in Proposition 5.1.

6 Application to a priori error estimates

In this section we show how to apply the results of Section 3 to the a priori error analysis of mixed finite element methods and least-squares mixed finite element methods for a model diffusion problem.

6.1 Mixed finite element methods

Let us consider the dual mixed finite element method for the Poisson model problem, following Raviart and Thomas [40], Nédélec [37], Roberts and Thomas [41], or Boffi *et al.* [7]. Let $f \in L^2(\Omega)$ and $\Gamma_{\mathrm{N}} = \emptyset$ for simplicity, so that $\boldsymbol{H}_{0,\Gamma_{\mathrm{N}}}(\mathrm{div},\Omega)$ becomes $\boldsymbol{H}(\mathrm{div},\Omega)$. Consider the Laplace problem of finding $u : \Omega \to \mathbb{R}$ such that

$$\begin{aligned} -\Delta u &= f && \text{in } \Omega, && (6.1a)\\ u &= 0 && \text{on } \partial\Omega. && (6.1b) \end{aligned}$$

The primal weak formulation of (6.1) reads: find $u \in H^1_0(\Omega)$ such that

$$(\nabla u, \nabla v) = (f, v) \qquad \forall v \in H^1_0(\Omega). \tag{6.2}$$

The dual weak formulation of (6.1) then reads: find $\boldsymbol{\sigma} \in \boldsymbol{H}(\mathrm{div},\Omega)$ and $u \in L^2(\Omega)$ such that

$$\begin{aligned} (\boldsymbol{\sigma}, \boldsymbol{v}) - (u, \nabla\cdot\boldsymbol{v}) &= 0 && \forall \boldsymbol{v} \in \boldsymbol{H}(\mathrm{div},\Omega), && (6.3a)\\ (\nabla\cdot\boldsymbol{\sigma}, q) &= (f, q) && \forall q \in L^2(\Omega). && (6.3b) \end{aligned}$$

Classically, u from (6.2) and (6.3) coincide and $\boldsymbol{\sigma} = -\nabla u$. The dual mixed finite element method of order $p \geq 0$ for the problem (6.3) then looks for the pair $\boldsymbol{\sigma}_{\mathrm{M}} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}(\mathrm{div},\Omega)$ and $u_{\mathrm{M}} \in \mathcal{P}_p(\mathcal{T})$ such that

$$\begin{aligned} (\boldsymbol{\sigma}_{\mathrm{M}}, \boldsymbol{\varsigma}_{\mathcal{T}}) - (u_{\mathrm{M}}, \nabla\cdot\boldsymbol{\varsigma}_{\mathcal{T}}) &= 0 && \forall \boldsymbol{\varsigma}_{\mathcal{T}} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}(\mathrm{div},\Omega), && (6.4a)\\ (\nabla\cdot\boldsymbol{\sigma}_{\mathrm{M}}, q_{\mathcal{T}}) &= (f, q_{\mathcal{T}}) && \forall q_{\mathcal{T}} \in \mathcal{P}_p(\mathcal{T}). && (6.4b) \end{aligned}$$

It is immediate to check from (6.3b) and (6.4b) that $\nabla\cdot\boldsymbol{\sigma}_{\mathrm{M}} = \Pi^p_{\mathcal{T}}(\nabla\cdot\boldsymbol{\sigma})$. Furthermore, the following a priori error characterization is classical, cf. [7]. We include its proof to highlight the precise arguments.

Lemma 6.1 (A priori bound for mixed finite element methods)**.** *Let $\boldsymbol{\sigma}_{\mathrm{M}}$ be the first component of the dual mixed finite element solution solving (6.4), approximating $\boldsymbol{\sigma}$ from (6.3). Then*

$$\|\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{M}}\| = \min_{\substack{\boldsymbol{\varsigma}_{\mathcal{T}} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}(\mathrm{div},\Omega) \\ \nabla\cdot\boldsymbol{\varsigma}_{\mathcal{T}} = \Pi^p_{\mathcal{T}}(\nabla\cdot\boldsymbol{\sigma})}} \|\boldsymbol{\sigma} - \boldsymbol{\varsigma}_{\mathcal{T}}\|.$$

Proof. Subtracting (6.4a) from (6.3a), we have

$$(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{M}}, \boldsymbol{\varsigma}_{\mathcal{T}}) - (u - u_{\mathrm{M}}, \nabla\cdot\boldsymbol{\varsigma}_{\mathcal{T}}) = 0 \quad \forall \boldsymbol{\varsigma}_{\mathcal{T}} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}(\mathrm{div}, \Omega). \tag{6.5}$$

Let $\boldsymbol{\sigma}_{\mathcal{T}} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}(\mathrm{div}, \Omega)$ be such that $\nabla\cdot\boldsymbol{\sigma}_{\mathcal{T}} = \Pi^p_{\mathcal{T}}(\nabla\cdot\boldsymbol{\sigma})$. Taking $\boldsymbol{\varsigma}_{\mathcal{T}} = \boldsymbol{\sigma}_{\mathcal{T}} - \boldsymbol{\sigma}_{\mathrm{M}}$ in (6.5), we obtain, since $\nabla\cdot\boldsymbol{\varsigma}_{\mathcal{T}} = 0$,

$$(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{M}}, \boldsymbol{\sigma}_{\mathcal{T}} - \boldsymbol{\sigma}_{\mathrm{M}}) = 0.$$

Now clearly

$$\|\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{M}}\|^2 = (\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{M}}, \boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{M}}) = (\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{M}}, \boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathcal{T}}) \le \|\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{M}}\|\, \|\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathcal{T}}\|,$$

and hence $\|\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{M}}\| \le \|\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathcal{T}}\|$. Since $\boldsymbol{\sigma}_{\mathcal{T}}$ is arbitrary subject to the divergence constraint and can be taken as $\boldsymbol{\sigma}_{\mathrm{M}}$, we obtain the assertion. □

Thus, $\|\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{M}}\|$ can be readily estimated by using Theorems 3.3 and 3.6.

6.2 Least-squares mixed finite element methods

In this subsection, we showcase the application of our results to the least-squares mixed finite element method discussed in Pehlivanov *et al.* [39], Cai and Ku [10], and Ku [33], see also the references therein.

Let again $\Gamma_{\mathrm{N}} = \emptyset$ for simplicity and $f \in L^2(\Omega)$. Let $\boldsymbol{\sigma} \in \boldsymbol{H}(\mathrm{div}, \Omega)$ and $u \in H^1_0(\Omega)$ be such that

$$(\boldsymbol{\sigma}, u) := \arg \min_{(\boldsymbol{p},v)\in \boldsymbol{H}(\mathrm{div},\Omega)\times H^1_0(\Omega)} \left\{ h_\Omega^2 \|\nabla\cdot\boldsymbol{p} - f\|^2 + \|\boldsymbol{p} + \nabla v\|^2 \right\},$$

where we recall that h_Ω is a length scale equal to the diameter of Ω. Then $\boldsymbol{\sigma} \in \boldsymbol{H}(\mathrm{div}, \Omega)$ and $u \in H^1_0(\Omega)$ solve the following system of equations:

$$(\boldsymbol{\sigma} + \nabla u, \nabla v) = 0 \qquad \forall v \in H^1_0(\Omega), \tag{6.6a}$$

$$h_\Omega^2(\nabla\cdot\boldsymbol{\sigma}, \nabla\cdot\boldsymbol{p}) + (\boldsymbol{\sigma} + \nabla u, \boldsymbol{p}) = h_\Omega^2(f, \nabla\cdot\boldsymbol{p}) \qquad \forall \boldsymbol{p} \in \boldsymbol{H}(\mathrm{div}, \Omega). \tag{6.6b}$$

Again, $\boldsymbol{\sigma}$ and u coincide with the solutions of (6.2) and (6.3). Let $p \ge 0$ and $q \ge 1$ denote two fixed polynomial degrees. The least-squares mixed finite element method for the problem (6.6) consists of finding $\boldsymbol{\sigma}_{\mathrm{LS}} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}(\mathrm{div}, \Omega)$ and $u_{\mathrm{LS}} \in \mathcal{P}^q(\mathcal{T}) \cap H^1_0(\Omega)$ such that

$$(\boldsymbol{\sigma}_{\mathrm{LS}} + \nabla u_{\mathrm{LS}}, \nabla v_{\mathcal{T}}) = 0 \qquad \forall v_{\mathcal{T}} \in \mathcal{P}^q(\mathcal{T}) \cap H^1_0(\Omega), \tag{6.7a}$$

$$h_\Omega^2(\nabla\cdot\boldsymbol{\sigma}_{\mathrm{LS}}, \nabla\cdot\boldsymbol{p}_{\mathcal{T}}) + (\boldsymbol{\sigma}_{\mathrm{LS}} + \nabla u_{\mathrm{LS}}, \boldsymbol{p}_{\mathcal{T}}) = h_\Omega^2(f, \nabla\cdot\boldsymbol{p}_{\mathcal{T}}) \qquad \forall \boldsymbol{p}_{\mathcal{T}} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}(\mathrm{div}, \Omega). \tag{6.7b}$$

Similarly to Lemma 6.1, we can obtain the following a priori error characterization.

Lemma 6.2 (A priori bound for least-squares mixed finite element methods)**.** *Let* $(\boldsymbol{\sigma}_{\mathrm{LS}}, u_{\mathrm{LS}})$ *be the least-squares mixed finite element solution pair solving* (6.7)*, approximating* $(\boldsymbol{\sigma}, u)$ *from* (6.6)*. Then there exists a generic constant* C*, at most equal to* 17*, such that*

$$\|\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{LS}}\| + \|\nabla(u - u_{\mathrm{LS}})\| \le C \left(\min_{\substack{\boldsymbol{\varsigma}_{\mathcal{T}} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}(\mathrm{div},\Omega) \\ \nabla\cdot\boldsymbol{\varsigma}_{\mathcal{T}} = \Pi^p_{\mathcal{T}}(\nabla\cdot\boldsymbol{\sigma})}} \|\boldsymbol{\sigma} - \boldsymbol{\varsigma}_{\mathcal{T}}\| + \min_{v_{\mathcal{T}} \in \mathcal{P}^q(\mathcal{T}) \cap H^1_0(\Omega)} \|\nabla(u - v_{\mathcal{T}})\| \right).$$

Proof. Define the bilinear form $\mathcal{A}$ on $(\boldsymbol{H}(\mathrm{div}, \Omega) \times H^1_0(\Omega)) \times (\boldsymbol{H}(\mathrm{div}, \Omega) \times H^1_0(\Omega))$ by

$$\mathcal{A}(\boldsymbol{\sigma}, u; \boldsymbol{p}, v) := (\boldsymbol{\sigma} + \nabla u, \nabla v) + h_\Omega^2(\nabla\cdot\boldsymbol{\sigma}, \nabla\cdot\boldsymbol{p}) + (\boldsymbol{\sigma} + \nabla u, \boldsymbol{p}).$$

We have the following orthogonality from (6.6) and (6.7):

$$\mathcal{A}(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{LS}}, u - u_{\mathrm{LS}}; \boldsymbol{p}_{\mathcal{T}}, v_{\mathcal{T}}) = 0 \tag{6.8}$$

for all $\boldsymbol{p}_{\mathcal{T}} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}(\mathrm{div}, \Omega)$ and for all $v_{\mathcal{T}} \in \mathcal{P}^q(\mathcal{T}) \cap H^1_0(\Omega)$. Moreover, the following coercivity is known from [39]: there exists a constant C such that

$$\mathcal{A}(\boldsymbol{p}, v; \boldsymbol{p}, v) \ge \frac{1}{C}\left(\|\boldsymbol{p}\|^2 + h_\Omega^2\|\nabla\cdot\boldsymbol{p}\|^2 + \|\nabla v\|^2\right) \qquad \forall (\boldsymbol{p}, v) \in \boldsymbol{H}(\mathrm{div}, \Omega) \times H^1_0(\Omega). \tag{6.9}$$

Indeed, owing to the Cauchy–Schwarz and Young inequalities, we have, for any $0 < \varepsilon < 2$,

$$\begin{aligned}\mathcal{A}(\boldsymbol{p}, v; \boldsymbol{p}, v) &= \|\nabla v\|^2 + (2-\varepsilon)(\boldsymbol{p}, \nabla v) + h_\Omega^2\|\nabla\cdot\boldsymbol{p}\|^2 + \|\boldsymbol{p}\|^2 + \varepsilon(\nabla v, \boldsymbol{p}) \\ &\geq \|\boldsymbol{p}\|^2 + \|\nabla v\|^2 - \frac{2-\varepsilon}{2}(\|\boldsymbol{p}\|^2 + \|\nabla v\|^2) + h_\Omega^2\|\nabla\cdot\boldsymbol{p}\|^2 - \varepsilon\|\nabla\cdot\boldsymbol{p}\|\|v\| \\ &\geq \frac{\varepsilon}{2}(\|\boldsymbol{p}\|^2 + \|\nabla v\|^2) + h_\Omega^2\|\nabla\cdot\boldsymbol{p}\|^2 - \varepsilon C_{\mathrm{PF}} h_\Omega\left(C_{\mathrm{PF}} h_\Omega\|\nabla\cdot\boldsymbol{p}\|^2 + \frac{1}{4C_{\mathrm{PF}} h_\Omega}\|\nabla v\|^2\right) \\ &= \frac{\varepsilon}{2}\|\boldsymbol{p}\|^2 + \frac{\varepsilon}{4}\|\nabla v\|^2 + \|\nabla\cdot\boldsymbol{p}\|^2\left(h_\Omega^2 - \varepsilon C_{\mathrm{PF}}^2 h_\Omega^2\right),\end{aligned}$$

where we have also employed the Green theorem $(\nabla v, \boldsymbol{p}) = -(\nabla\cdot\boldsymbol{p}, v)$ and the Poincaré–Friedrichs inequality $\|v\| \leq C_{\mathrm{PF}} h_\Omega \|\nabla v\|$ (here h_Ω is the diameter of Ω and $C_{\mathrm{PF}} \leq 1$ a generic constant). The assertion (6.9) follows by choosing, e.g., $\varepsilon = h_\Omega^2/(2C_{\mathrm{PF}}^2 h_\Omega^2)$. Note that, employing $C_{\mathrm{PF}} = 1$, the constant C in (6.9) can be taken as 8.

Let now $\boldsymbol{\varsigma}_{\mathcal{T}} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}(\mathrm{div}, \Omega)$ be such that $\nabla\cdot\boldsymbol{\varsigma}_{\mathcal{T}} = \Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{\sigma})$ and $v_{\mathcal{T}} \in \mathcal{P}^q(\mathcal{T}) \cap H_0^1(\Omega)$ be an arbitrary function. Set $q_{\mathcal{T}} := v_{\mathcal{T}} - u_{\mathrm{LS}}$ and $\boldsymbol{p}_{\mathcal{T}} := \boldsymbol{\varsigma}_{\mathcal{T}} - \boldsymbol{\sigma}_{\mathrm{LS}}$. Then using (6.8) and (6.9), we find

$$\begin{aligned}\frac{1}{C}\left(\|\boldsymbol{p}_{\mathcal{T}}\|^2 + \|\nabla q_{\mathcal{T}}\|^2\right) &\leq \mathcal{A}(\boldsymbol{\varsigma}_{\mathcal{T}} - \boldsymbol{\sigma}_{\mathrm{LS}}, v_{\mathcal{T}} - u_{\mathrm{LS}}; \boldsymbol{p}_{\mathcal{T}}, q_{\mathcal{T}}) \\ &= \mathcal{A}(\boldsymbol{\varsigma}_{\mathcal{T}} - \boldsymbol{\sigma}, v_{\mathcal{T}} - u; \boldsymbol{p}_{\mathcal{T}}, q_{\mathcal{T}}) \\ &= (\boldsymbol{\varsigma}_{\mathcal{T}} - \boldsymbol{\sigma} + \nabla(v_{\mathcal{T}} - u), \nabla q_{\mathcal{T}}) + h_\Omega^2(\nabla\cdot(\boldsymbol{\varsigma}_{\mathcal{T}} - \boldsymbol{\sigma}), \nabla\cdot\boldsymbol{p}_{\mathcal{T}}) \\ &\quad + (\boldsymbol{\varsigma}_{\mathcal{T}} - \boldsymbol{\sigma} + \nabla(v_{\mathcal{T}} - u), \boldsymbol{p}_{\mathcal{T}}).\end{aligned}$$

Since $\nabla\cdot\boldsymbol{\varsigma}_{\mathcal{T}} = \Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{\sigma})$ and $\nabla\cdot\boldsymbol{p}_{\mathcal{T}} \in \mathcal{P}^p(\mathcal{T})$, we have $(\nabla\cdot(\boldsymbol{\varsigma}_{\mathcal{T}} - \boldsymbol{\sigma}), \nabla\cdot\boldsymbol{p}_{\mathcal{T}}) = 0$. Using the Cauchy–Schwarz and the Young inequality, we then obtain, with the constant C from (6.9),

$$\|\boldsymbol{p}_{\mathcal{T}}\| + \|\nabla q_{\mathcal{T}}\| \leq 2C\left(\|\boldsymbol{\sigma} - \boldsymbol{\varsigma}_{\mathcal{T}}\| + \|\nabla(u - v_{\mathcal{T}})\|\right),$$

which proves the claim owing to the triangle inequality and since $\boldsymbol{\varsigma}_{\mathcal{T}}$ and $v_{\mathcal{T}}$ are arbitrary. $\square$

The two terms in the error bound from Lemma 6.2 are uncoupled. For the first one, we can again straightforwardly use Theorems 3.3 and 3.6. For the second one, the result of Veeser [45] yields

$$\min_{v_{\mathcal{T}} \in \mathcal{P}^q(\mathcal{T}) \cap H_0^1(\Omega)} \|\nabla(u - v_{\mathcal{T}})\|^2 \leq C \sum_{K \in \mathcal{T}} \min_{q_K \in \mathcal{P}^q(K)} \|\nabla(u - q_K)\|_K^2,$$

where the constant C depends only on the space dimension d, the shape-regularity parameter $\kappa_{\mathcal{T}}$ of $\mathcal{T}$, and the polynomial degree q, which is again optimal.

Finally, a localized estimate for the error $\nabla\cdot(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{LS}})$ follows by the combination of the above results with the following lemma.

Lemma 6.3 (A priori bound on the divergence for least-squares mixed finite element methods)**.** *Let* $(\boldsymbol{\sigma}_{\mathrm{LS}}, u_{\mathrm{LS}})$ *be the least-squares mixed finite element solution solving* (6.7)*, approximating* $(\boldsymbol{\sigma}, u)$ *from* (6.6)*. Then*

$$\begin{aligned}h_\Omega^2\|\nabla\cdot(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{LS}})\|^2 &\leq h_\Omega^2\|\nabla\cdot\boldsymbol{\sigma} - \Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{\sigma})\|^2 + \|\nabla(u - u_{\mathrm{LS}})\|^2 \\ &\quad + \min_{\substack{\boldsymbol{\varsigma}_{\mathcal{T}} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}(\mathrm{div}, \Omega) \\ \nabla\cdot\boldsymbol{\varsigma}_{\mathcal{T}} = \Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{\sigma})}} \|\boldsymbol{\sigma} - \boldsymbol{\varsigma}_{\mathcal{T}}\|^2.\end{aligned}$$

Proof. Again let $\boldsymbol{\sigma}_{\mathcal{T}} \in \boldsymbol{RTN}_p(\mathcal{T}) \cap \boldsymbol{H}(\mathrm{div}, \Omega)$ be such that $\nabla\cdot\boldsymbol{\sigma}_{\mathcal{T}} = \Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{\sigma})$. Using (6.6b) and (6.7b), we have

$$\begin{aligned}h_\Omega^2\|\nabla\cdot(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{LS}})\|^2 &= h_\Omega^2(\nabla\cdot(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{LS}}), \nabla\cdot(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{LS}})) \\ &= h_\Omega^2(\nabla\cdot(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{LS}}), \nabla\cdot(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathcal{T}})) + h_\Omega^2(\nabla\cdot(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{LS}}), \nabla\cdot(\boldsymbol{\sigma}_{\mathcal{T}} - \boldsymbol{\sigma}_{\mathrm{LS}})) \\ &= h_\Omega^2(\nabla\cdot(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{LS}}), \nabla\cdot(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathcal{T}})) + h_\Omega^2(\nabla\cdot(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{LS}}), \nabla\cdot(\boldsymbol{\sigma}_{\mathcal{T}} - \boldsymbol{\sigma}_{\mathrm{LS}})) \\ &\quad - \mathcal{A}(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{LS}}, u - u_{\mathrm{LS}}; \boldsymbol{\sigma}_{\mathcal{T}} - \boldsymbol{\sigma}_{\mathrm{LS}}, 0) \\ &= h_\Omega^2(\nabla\cdot(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{LS}}), \nabla\cdot(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathcal{T}})) - ((\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{LS}}) + \nabla(u - u_{\mathrm{LS}}), \boldsymbol{\sigma}_{\mathcal{T}} - \boldsymbol{\sigma}_{\mathrm{LS}}) \\ &= h_\Omega^2(\nabla\cdot(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathcal{T}}), \nabla\cdot(\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathcal{T}})) - ((\boldsymbol{\sigma} - \boldsymbol{\sigma}_{\mathrm{LS}}) + \nabla(u - u_{\mathrm{LS}}), \boldsymbol{\sigma}_{\mathcal{T}} - \boldsymbol{\sigma}_{\mathrm{LS}}),\end{aligned}$$

where we used that $(\nabla\cdot\boldsymbol{\sigma}_{\mathrm{LS}}, \nabla\cdot(\boldsymbol{\sigma}-\boldsymbol{\sigma}_{\mathcal{T}})) = (\nabla\cdot\boldsymbol{\sigma}_{\mathcal{T}}, \nabla\cdot(\boldsymbol{\sigma}-\boldsymbol{\sigma}_{\mathcal{T}})) = 0$ since both $\nabla\cdot\boldsymbol{\sigma}_{\mathrm{LS}}$ and $\nabla\cdot\boldsymbol{\sigma}_{\mathcal{T}}$ belong to $\mathcal{P}_p(\mathcal{T})$ in the last equality. Adding and subtracting $\boldsymbol{\sigma}$ in the second term on the right-hand side above and applying the Cauchy–Schwarz and Young inequalities implies that

$$\begin{aligned}
&h_\Omega^2\|\nabla\cdot(\boldsymbol{\sigma}-\boldsymbol{\sigma}_{\mathrm{LS}})\|^2 + \|\boldsymbol{\sigma}-\boldsymbol{\sigma}_{\mathrm{LS}}\|^2 \\
&= h_\Omega^2\|\nabla\cdot\boldsymbol{\sigma} - \Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{\sigma})\|^2 - (\nabla(u-u_{\mathrm{LS}}), \boldsymbol{\sigma}-\boldsymbol{\sigma}_{\mathrm{LS}}) \\
&\quad - (\nabla(u-u_{\mathrm{LS}}), \boldsymbol{\sigma}_{\mathcal{T}}-\boldsymbol{\sigma}) - (\boldsymbol{\sigma}-\boldsymbol{\sigma}_{\mathrm{LS}}, \boldsymbol{\sigma}_{\mathcal{T}}-\boldsymbol{\sigma}) \\
&\le h_\Omega^2\|\nabla\cdot\boldsymbol{\sigma} - \Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{\sigma})\|^2 + \|\nabla(u-u_{\mathrm{LS}})\|^2 + \|\boldsymbol{\sigma}-\boldsymbol{\sigma}_{\mathcal{T}}\|^2 + \|\boldsymbol{\sigma}-\boldsymbol{\sigma}_{\mathrm{LS}}\|^2.
\end{aligned}$$

We infer that

$$h_\Omega^2\|\nabla\cdot(\boldsymbol{\sigma}-\boldsymbol{\sigma}_{\mathrm{LS}})\|^2 \le h_\Omega^2\|\nabla\cdot\boldsymbol{\sigma} - \Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{\sigma})\|^2 + \|\nabla(u-u_{\mathrm{LS}})\|^2 + \|\boldsymbol{\sigma}-\boldsymbol{\sigma}_{\mathcal{T}}\|^2.$$

This finishes the proof since $\boldsymbol{\sigma}_{\mathcal{T}}$ is arbitrary. □

A p-robust constrained–unconstrained equivalence on a simplex

We present in this appendix a way to remove the divergence constraint on a single simplex, and we do this in a polynomial-degree-robust way. This equivalence of constrained and unconstrained local-best approximations is an important consequence of the result of Costabel and McIntosh [16, Corollary 3.4].

Recall the notation $e_{K,p}(\boldsymbol{v})$ from (3.11), where $\boldsymbol{RTN}_p(K) = \mathcal{P}_p(K;\mathbb{R}^d) + \boldsymbol{x}\mathcal{P}_p(K)$ is the Raviart–Thomas–Nédélec space of degree p on the simplex K, as well as that h_K denotes the diameter of K and ϱ_K the diameter of the largest ball inscribed in K.

Lemma A.1 (Local p-robust constrained–unconstrained equivalence)**.** *Let a simplex $K \subset \mathbb{R}^d$, $d \ge 1$, and $\boldsymbol{v} \in \boldsymbol{H}(\mathrm{div};K)$ be fixed. Let $\boldsymbol{\tau}_{\mathcal{T}}$ be defined as in (3.1). Then, there exists a constant C, depending only on the space dimension d and the shape-regularity parameter $\kappa_K := h_K/\varrho_K$ of K, such that*

$$e_{K,p}(\boldsymbol{v}) \le \|\boldsymbol{v}-\boldsymbol{\tau}_{\mathcal{T}}\|_K + \frac{h_K}{p+1}\|\nabla\cdot(\boldsymbol{v}-\boldsymbol{\tau}_{\mathcal{T}})\|_K \le C e_{K,p}(\boldsymbol{v}). \tag{A.1}$$

Proof. Since $\nabla\cdot\boldsymbol{\tau}_{\mathcal{T}} = \Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{v})$ from (3.1), the first inequality in (A.1) is obvious, so we show the second one. Therein, $\frac{h_K}{p+1}\|\nabla\cdot(\boldsymbol{v}-\boldsymbol{\tau}_{\mathcal{T}})\|_K \le e_{K,p}(\boldsymbol{v})$ trivially holds true for the same reason, so it remains only to bound $\|\boldsymbol{v}-\boldsymbol{\tau}_{\mathcal{T}}\|_K$.

Let $\widetilde{\boldsymbol{\tau}}_{\mathcal{T}}$ be the elementwise $\boldsymbol{L}^2$-projection of $\boldsymbol{v}$ into $\boldsymbol{RTN}_p(\mathcal{T})$, so that

$$[e_{K,p}(\boldsymbol{v})]^2 = \|\boldsymbol{v}-\widetilde{\boldsymbol{\tau}}_{\mathcal{T}}\|_K^2 + \frac{h_K^2}{(p+1)^2}\|\nabla\cdot\boldsymbol{v} - \Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{v})\|_K^2.$$

It follows from [16, Corollary 3.4] that there exists $\boldsymbol{\varsigma}_K \in \boldsymbol{RTN}_p(K)$ such that $\nabla\cdot\boldsymbol{\varsigma}_K = \Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{v})$ and

$$\|\boldsymbol{\varsigma}_K - \widetilde{\boldsymbol{\tau}}_{\mathcal{T}}\|_K \le C \sup_{\substack{\varphi\in H_0^1(K)\\ \|\nabla\varphi\|_K=1}} \left\{(\Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{v}) - \nabla\cdot\widetilde{\boldsymbol{\tau}}_{\mathcal{T}}, \varphi)_K\right\}, \tag{A.2}$$

where C only depends on d and κ_K. Since $(\nabla\cdot\boldsymbol{v},\varphi)_K + (\boldsymbol{v},\nabla\varphi)_K = 0$, and since also $(\nabla\cdot\widetilde{\boldsymbol{\tau}}_{\mathcal{T}},\varphi)_K + (\widetilde{\boldsymbol{\tau}}_{\mathcal{T}},\nabla\varphi)_K = 0$ for all $\varphi \in H_0^1(K)$, we see that

$$(\Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{v}),\varphi)_K - (\nabla\cdot\widetilde{\boldsymbol{\tau}}_{\mathcal{T}},\varphi)_K = (\Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{v}) - \nabla\cdot\boldsymbol{v}, \varphi - \Pi_{\mathcal{T}}^p(\varphi))_K - (\boldsymbol{v}-\widetilde{\boldsymbol{\tau}}_{\mathcal{T}},\nabla\varphi)_K,$$

where we have also freely subtracted $\Pi_{\mathcal{T}}^p(\varphi)$. Therefore, the inequality (A.2) combined with the approximation bound $\|\varphi - \Pi_{\mathcal{T}}^p(\varphi)\|_K \le C\frac{h_K}{p+1}\|\nabla\varphi\|_K$, with a constant C depending only on d and κ_K, implies that

$$\|\boldsymbol{\varsigma}_K - \widetilde{\boldsymbol{\tau}}_{\mathcal{T}}\|_K \le C\left\{\|\boldsymbol{v}-\widetilde{\boldsymbol{\tau}}_{\mathcal{T}}\|_K^2 + \left[\frac{h_K}{p+1}\|\nabla\cdot\boldsymbol{v} - \Pi_{\mathcal{T}}^p(\nabla\cdot\boldsymbol{v})\|_K\right]^2\right\}^{\frac{1}{2}} = C e_{K,p}(\boldsymbol{v}).$$

Finally, owing to the triangle inequality $\|\boldsymbol{v}-\boldsymbol{\varsigma}_K\|_K \le \|\boldsymbol{v}-\widetilde{\boldsymbol{\tau}}_{\mathcal{T}}\|_K + \|\widetilde{\boldsymbol{\tau}}_{\mathcal{T}} - \boldsymbol{\varsigma}_K\|_K$, we infer that $\|\boldsymbol{v}-\boldsymbol{\varsigma}_K\|_K \le C e_{K,p}(\boldsymbol{v})$. Consequently, the definition of $\boldsymbol{\tau}_{\mathcal{T}}$ as the minimizer in (3.1) implies that $\|\boldsymbol{v}-\boldsymbol{\tau}_{\mathcal{T}}\|_K \le \|\boldsymbol{v}-\boldsymbol{\varsigma}_K\|_K$, and this yields the second bound in (A.1). □

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