

RESEARCH ARTICLE

Comparing risk adjustment estimation methods under data availability constraints

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Abstract

The Italian National Healthcare Service relies on per capita allocation for healthcare funds, despite having a highly detailed and wide range of data to potentially build a complex risk-adjustment formula. However, heterogeneity in data availability limits the development of a national model. This paper implements and evaluates machine learning (ML) and standard risk-adjustment models on different data scenarios that a Region or Country may face, to optimize information with the most predictive model. We show that ML achieves a small but generally statistically insignificant improvement of adjusted R^2 and mean squared error with fine data granularity compared to linear regression, while in coarse granularity and poor range of variables scenario no differences were observed. The advantage of ML algorithms is greater in the coarse granularity and fair/rich range of variables set and limited with fine granularity scenarios. The inclusion of detailed morbidity- and pharmacy-based adjusters generally increases fit, although the trade-off of creating adverse economic incentives must be considered.

KEYWORDS

data granularity, formula funding, health expenditure, machine learning, risk-adjustment

1 | INTRODUCTION

In middle- and high-income countries, health expenditure has steadily increased over time, making its containment a major issue for governments: policymakers must control healthcare resources to efficiently address population aging and public budget constraints. Risk-adjustment schemes are one such tool for managing the efficiency and fairness of healthcare spending (Cid et al., 2016). The primary statistical purpose of risk-adjustment models, both in a health plan payment or provider reimbursement, is to accurately predict individual healthcare costs. When designing a risk-adjustment program, policymakers should aim to optimize the choice of statistical methods based on their data availability in the short-medium term, pending a longer-term investment to expand the range of variables and level of detail.

The performance of a risk-adjustment algorithm depends not only on the model or functional form, but also on the underlying data. In a setting with decentralized data administration, differences in data collection – and thus in the data available for prediction – stem from several sources, including: the accessibility of distinct databases (inpatient, pharmaceutical, outpatient services), the range of data elements collected, the ability to merge information at an individual level (due to privacy

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regulations), and different quality standards or level of detail in data collection (rudimentary vs. advanced information systems) according to the local context (we refer to the level of detail or aggregation as the “granularity” of the data).

The Italian National Healthcare Service (NHS) is an example of a healthcare system with substantial heterogeneity in data collection. With its decentralized units (21 health regions) all subject to the same national legislation regarding data collection duties, the Italian NHS has the potential for using a highly detailed and wide-ranging set of information to predict individual health expenditure. However, data collection takes place at the local level, where there are differing capacities to combine healthcare administrative databases, heterogeneous information systems, and variability in data granularity and quality control (Skrami et al., 2019). Thus, despite this potential richness of individual health information, the allocation of Italian NHS resources to Regions is still based on age-weighted capitation. Per capita allocation using synthetic indices methods or actuarial cells formulas is common among national health systems (e.g., Spain, Denmark, Scotland, Portugal) to distribute resources in a large geographical area for its simplicity of construction and low cost information (Cid et al., 2016). However, person-based formulae are increasingly used as an alternative method (e.g., United Kingdom), and they offer considerable scope for ensuring equitable allocations of health budgets to geographical areas (Radinmanesh et al., 2021; Smith, 2006).

In this paper, we develop a framework for designing an effective risk-adjustment algorithm to predict total healthcare expenditure by using routinely available, person-based Italian data on health needs. We explore different data scenarios by examining how the predictive performance of conventional and machine learning (ML) risk-adjustment estimation varies across by data granularity and range of variables settings.

Our primary contribution is to develop general guidelines for policymakers who have various scenarios of data granularity and/or range of variables and to provide a set of applicable statistical tools. For countries with national health systems this study may serve as a basis for budget setting using person-based regression models, which are more predictive than synthetic indices methods or actuarial cells formulas because they capture more variability in patient needs (Ellis, 2007). Countries with data constraints may use our framework to optimize the information available to improve efficiency and fairness in allocating resources or to reduce incentives for risk-selection (Henríquez et al., 2020). Countries with less limiting data constraints can implement more sophisticated ML techniques to improve predictive performances and fit efficiency (Geruso & McGuire, 2016; Kronick & Welch, 2014; Rose, 2016).

2 | EMPIRICAL FRAMEWORK

In Table 1 we present six typical data scenarios to predict total healthcare expenditure, which varies in two dimensions: range of variables (the number of health databases), and data granularity (the detail of the information in each database). These scenarios are based on real-world implementations of risk-adjustment programs and data collection; it is common to begin with age-sex cells, then add in hospitalization information, and finally pharmaceutical data. Similarly, a coarser level of detail may be more amenable to basic data collection and simpler prediction methods. The Italian health information system is theoretically located in the cell at the bottom right (fine data/rich range of variables), but as long as the reliability and consistency of the administrative databases is uncertain, the first cell at the top left (coarse data/poor range of variables) could be the first plausible scenario in the transition from synthetic indices methods to more predictive models.

We use “range of variables” to refer to the data availability with respect to different health areas, and with “data granularity” we refer to the detail available. Age and sex are optimal exogenous risk-adjusters because they cannot be influenced by health providers' actions. However, they do not accurately reflect the epidemiological variability and health needs among geographical areas (Atella et al., 2018). Since the late 1990s, the United States (US) and many European health systems expanded the range of variables to reduce risk selection with increasingly sophisticated risk-adjustment formulas, including socio-economic, pharmacy- and diagnosis-based indicators (Ellis et al., 2018). Diagnosis information may be endogenous to some extent but is generally far more predictive than age and sex alone. In the UK, factors capturing demography, morbidity, deprivation, and unavoidable cost of providing services in different areas have been included in a complex person-based formula to improve the allocation of the “fair share” for each area (Dixon et al., 2011).

Early studies in the US demonstrated the inclusion of diagnosis cost groups (DCGs) improved the R^2 of the demographic model (age-sex data) by 40% points in a concurrent model and by 10% points in a prospective model (Ellis et al., 1996; Pope et al., 2000). A study for allocating commissioning funds to general practices in England, showed that from a model with age and sex only, adding diagnostic-related variables improved predictive power from 3.7% to 12.6% at individual level (Dixon et al., 2011).

In 2002, the Dutch health system was the first to expand the range of variables with pharmaceutical data through the Pharmacy-based Cost Group (PCG), a risk-adjuster based on pharmaceutical use, which increased the R^2 from 4% in the

TABLE 1 Data setting scenarios to predict total health care expenditure

	Poor range of variables	Fair range of variables	Rich range of variables
	Demographic (DEM)	DEM + hospital discharge records (HDR)	DEM + HDR + pharmacy database (PD)
Coarse granularity (sparse detail)	<i>Total health care costs = $f(\text{sex} * \text{age groups})$</i> Age groups: 0, 1–4, 5-year classes up to 90, 90+	<i>Total health care costs = $f(\text{sex} * \text{age groups} + \text{n. of hospitalizations})$</i> HDR: N. of hospitalizations	<i>Total health care costs = $f(\text{sex} * \text{age groups} + \text{n. of hospitalizations} + \text{n. of drug prescriptions})$</i> HDR: N. of hospitalizations PD: N. of prescriptions
Fine granularity (high detail)	<i>Total health care costs = $f(\text{sex} * \text{age groups} + \text{citizenship} + \text{degree of urbanization} + \text{income})$</i> Age groups: 0, 1–4, 5-year classes up to 90, 90+ Citizenship: Italian (yes/no) Degree of urbanization: Urban, peri-urban, rural Income: low, medium-low, medium high, high	<i>Total health care costs = $f(\text{sex} * \text{age groups} + \text{citizenship} + \text{municipality of residence} + \text{income} + \text{group of ICD-9 codes})$</i> HDR: ICD-9-CM codes which can be classified into diagnosis-related groups ^a	<i>Total health care costs = $f(\text{sex} * \text{age groups} + \text{citizenship} + \text{municipality of residence} + \text{income} + \text{group of ICD-9 codes} + \text{group of ATC codes})$</i> HDR: ICD-9-CM codes; may be classified into DCGs PD: ATC codes; may be classified into PCGs ^b

Abbreviations: ESRD, End-Stage Renal Disease; HCC, Hierarchical Condition Category; HDR, hospital discharge records; PD, pharmacy database; RxHCC, Prescription Drug Hierarchical Condition Category.

^aFor example, possible coding classification systems include the Clinical Classifications Software for ICD-9-CM (<https://www.hcup-us.ahrq.gov/toolssoftware/ccs/ccs.jsp>) or the 2015 Risk Adjustment model software HCC, RxHCC, ESRD of Centers for Medicare & Medicaid Services (<https://www.cms.gov/Medicare/Health-Plans/MedicareAdvtgSpecRateStats/Risk-Adjustors>) or the DCG.

^bFor example, Pharmacy Cost-Group (PCG).

demographic model to almost 9% (Lamers, 1999). In 2017, the sophisticated prospective Dutch risk-adjustment model reached an R^2 of almost 32% (van Kleef et al., 2018).

Other countries with competitive insurance markets have introduced morbidity indicators in their risk adjustment modeling, albeit with some limitations. Switzerland introduced PCGs into risk-adjustment modeling after a study found that the inclusion of pharmaceutical indicators in the Swiss prospective formula increases the R^2 by 13% points (Schmid & Beck, 2016), while diagnostic information is still incorporated as a dummy variable (yes/no prior hospitalizations). Germany uses pharmaceutical data to validate or impute missing diagnoses, while the Netherlands does not include outpatient diagnoses in the risk-adjustment systems (Bauhoff et al., 2017). Most US risk-adjustment systems do not use pharmaceutical data as predictors for health care expenditure (except Marketplaces), although Wagner et al. showed the DxCG system (supported by Verisk, a commonly used proprietary risk adjustment systems for cost data), which computes risk score using pharmacy and hospital data, increased the R^2 estimates by 8 to 20% points compared to the base models without pharmacy data (Wagner et al., 2016).

Despite the development of indicators based on diagnosis and pharmaceutical data, which have substantially improved the predictive performance of risk-adjustment algorithms over the past 2 decades, data constraints are still present in many countries. In Italy, approximately 35% (outpatient service and half of hospital expenditure) of the Italian National Health Fund is distributed to Regions based on an age-weighting system, while the remainder is allocated based on the unweighted resident population (Ferre et al., 2014). Ireland's health system relies on age, gender, and level of coverage as risk adjusters to determine transfers under risk equalization (Armstrong, 2018); Australian and Chilean risk equalization formulas are based on age, gender, and location (Paolucci et al., 2018; Velasco et al., 2018).

3 | NEW RISK-ADJUSTMENT ESTIMATION TECHNIQUES

Ordinary least squares (OLS) is the tool most commonly used in practice to predict healthcare spending (Ellis et al., 2018; Iezzoni, 2012). Recent literature has explored deploying ML methods, particularly in health systems with fine data and rich range of variables. The exponential growth of the size and complexity of electronic health information and the advancement

in computational capacity has shifted the attention of health statisticians and econometricians towards newer techniques (Rose, 2016). These techniques allow for the automated investigation of all possible covariates available and to leverage the complex structure of population-level health data (Kan et al., 2019).

Rose (2016) compared OLS with 8 ML algorithms (lasso, ridge, elastic net, neural net, single tree, random forests (RF), and a discrete and weighted super learner (SL)) using the inputs of the official US individual Marketplace risk-adjustment formula, including age, sex, geographic area, 5 inpatient diagnosis categories, and 74 Hierarchical Condition Category (HCC) variables, to predict total annual expenditures in a prospective formula. The results highlighted the minor improvement in performance of the SL with respect to cross-validated R^2 , but also showed that reducing the number of covariates to 10 only marginally reduced the predictive performance, providing preliminary evidence that few variables could yield effective plan payment risk-adjustment. McGuire, Zink, and Rose (McGuire et al., 2020) examined payment system fit with a concurrent formula in the setting of the US individual Marketplaces. The study found a penalized regression with age and sex cells and 30 HCCs performed similarly to the baseline linear regression with age and sex cells and 90+ HCC-based variables, while pharmaceutical covariates did not improve fit over the diagnosis-based risk adjusters. In recent work, Kan et al. (2019) compared OLS and penalized linear regressions for predicting Medicare Advantage health care expenditure (patients aged ≥ 65 years). The authors emphasized the advantages of penalized regressions, particularly the lasso, which yielded improvements over OLS in a single year of data and a 4-year pooled-data setting.

In non-US settings, exploration of interaction terms has been common. Buchner et al. employed a regression tree analysis to improve the German risk-adjustment formula with significant interactions between variables (Buchner et al., 2017). The inclusion of morbidity interaction terms showed a marginal improvement of R^2 , with an insubstantial loss in accuracy. Examining the 2014 Dutch risk-adjustment formula, van Veen et al. (van Veen et al., 2018) found that a similar approach improved the adjusted R^2 , but concluded it may also increase the possibility of risk-selection for some subgroups.

4 | DATA

Our study population was drawn from the 2016 administrative databases of Emilia, a Northern Italian Region with about 4.4 million beneficiaries with universal access to the Italian NHS.

The main databases used were:

1. Hospital Discharge Records: Admissions and discharge dates; primary and up to five secondary diagnoses and up to six interventions (ICD-9-CM coding system) are included. Expenditure is registered using the diagnosis-related group tariffs system since 1995 (Emilia-Romagna, 2014).
2. Outpatient Pharmaceutical Database (OPD): Contains drugs reimbursed by the NHS (prescribed by the primary care physician or a specialist, or directly dispensed by the hospital pharmacies) and details on substance name, Anatomical Therapeutic Chemical (ATC) classification system code-V.2013, brand name, date of prescription filling, number of unit doses and number of packages and prescribers.
3. Outpatient Speciality Database (OSD): Contains individual expenditures of laboratory test and specialistic visits.

The linkage among these databases was possible through a unique anonymized patient identifier. We include only individuals who were residents in 2016 of one of the 8 Local Health Authorities of Emilia-Romagna.

4.1 | Socio-demographic covariates

We included gender, age (divided into 20 classes: 0, 1-4, 5-year classes up to 90 years and a class open over 90 years), citizenship (dichotomous variable: Italian yes/no), the degree of urbanization of residence (classified using the Eurostat's Degree of Urbanization (DEGURBA) (Eurostat, 2014) classification system into sparsely populated areas, intermediate density areas, and densely populated areas) and the income derived from the exemptions (if an individual presented more than one exemption they were assigned to the lowest income class).

4.2 | Hospital covariates

The hospital covariates included the total number of hospitalization and ICD-9-CM codes, which were grouped into DCGs. This method, originally proposed by Ash and colleagues (Ash et al., 1989; Ellis & Ash, 1995), first aggregates the diagnostic codes into 78 clinically homogeneous subgroups, then further aggregates these subgroups into 9 large groups on the basis of their equivalence in terms of resource absorption. Individuals with multiple diagnoses were classified only in their most expensive DCG while individuals without any diagnoses were grouped into DCG 0. Appendix Table A contains the full list of DCGs.

4.3 | Pharmacy covariates

From the OPD, we included the total number of drug prescriptions and ATC codes, which we grouped into PCGs. Through the ATC coding system, individuals with pharmaceutical prescriptions in 1 year are marked with a medical condition, which is then used as risk adjuster for the distribution of the resources thereafter. For the construction of the PCGs, we combined the Dutch model and other approaches that use the ATC codes to identify patients with chronic condition from the pharmaceutical databases defining 36 distinct classes (Chini et al., 2011; Corrao et al., 2017; Trottmann et al., 2010; Trottmann et al., 2015). An individual is classified into a PCG if the year amount of defined daily doses (DDD) in a given pharmaceutical class was greater than 180 DDD (cancer drugs required only >15 DDD). The full list of PCGs is shown Appendix Table B.

4.4 | Dependent variable

The outcome of interest is annual total expenditure, calculated by summing up the expenditures of hospital, pharmaceutical, and outpatient care services provided to residents of Emilia-Romagna Region during 2016.

We implemented a concurrent risk-adjustment approach: health care expenditure was predicted by individual characteristics from the same year. The concurrent method, compared to the prospective, reduces the data burden by using only a single year of data and does not require a separate formula for individuals with no information from the prior year. Concurrent risk models generally yield higher predictive power than prospective models. The compromise of this higher predictiveness is a reduced incentive to control healthcare spending and a longer timeline for payment, adding uncertainty, administrative burdens, and planning challenges (Geruso & McGuire, 2016).

4.5 | Characteristics of the population

A summary of socio-demographic variables is presented in Table 2. There were slightly more women than men in the sample (52%) and the largest age groups were 50–54 (9.2%) and 45–49 (9.1%). Mean total healthcare expenditure was 834€. Women had a slightly lower mean expenditure compared to men (832 vs. 841€) but a much higher median expenditure (114 vs. 59€). Italians had higher mean expenditure than non-Italians (861 vs. 530€) and people who lived in rural areas had higher expenditure (876€) than those living in urban (858€) or peri-urban areas (796€). Low-income exempted individuals had the highest mean and median expenditure (1161 and 226€) compared with other income groups. Average spending increased with more hospitalizations or prescriptions. Similarly, individuals with DCG were more expensive (5631€) than individuals with no DCG (227€), as well for individuals with at least one PCG (1729 €) compared to those with no PCG (406 €).

5 | STATISTICAL ANALYSIS

5.1 | Model specifications

As our baseline method, we implemented an OLS regression. To account for the highly skewed distribution of healthcare spending, we also estimated generalized linear models, using the frequently applied log-link function and two distribution families (Gaussian and Gamma; Jones, 2010).

TABLE 2 Description of the study population ($n = 4,262,982$)

	Total expenditure in 2016						
	N	% Col	Mean	S. D.	25 th perc	Median	75 th perc
Observations	4,262,982	100%	834.0	3306.0	13	87	405
Male	2,054,695	48.2%	838.2	3618.0	6	59	344
Female	2,208,287	51.8%	829.8	2986.9	24	114	460
Age groups							
0	48,632	1.1%	1358.1	4832.4	128	340	416
1–4	119,804	2.8%	234.6	1875.0	11	30	82
5–9	157,598	3.7%	167.7	1339.2	7	21	65
10–14	153,215	3.6%	201.9	1448.7	6	29	99
15–19	144,999	3.4%	244.1	1873.1	5	24	98
20–24	148,695	3.5%	286.8	1870.2	3	22	91
25–29	184,774	4.3%	322.5	1795.3	4	26	111
30–34	225,961	5.3%	358.4	1730.4	5	31	131
35–39	279,342	6.6%	374.3	1925.0	5	31	138
40–44	353,249	8.3%	384.8	2267.9	2	32	141
45–49	389,168	9.1%	424.2	2359.5	4	48	172
50–54	391,461	9.2%	528.0	2883.7	4	57	223
55–59	313,161	7.3%	743.2	3579.0	18	103	337
60–64	266,900	6.3%	1008.0	3978.9	40	172	497
65–69	273,682	6.4%	1378.1	4351.7	101	318	809
70–74	224,178	5.3%	1771.5	4675.0	173	459	1145
75–79	226,081	5.3%	2077.4	5020.8	237	568	1414
80–84	173,644	4.1%	2277.6	4929.6	287	638	1690
85–89	116,705	2.7%	2325.1	4592.5	275	617	2082
90+	71,733	1.7%	2225.8	4002.1	205	506	2713
Italian citizenship							
No	351,815	8.3%	529.9	2761.0	8	50	220
Yes	3,911,167	91.7%	861.2	3349.5	13	92	425
Degree of urbanization							
Urban	1,548,231	36.3%	857.8	3418.7	11	84	406
Peri-urban	1,896,501	44.5%	796.1	3191.1	13	83	385
Rural	818,250	19.2%	875.9	3350.3	17	102	450
Income							
Exempt low income	1,746,677	41.0%	1161.1	3576.4	54	226	735
Exempt middle-low income	583,624	13.7%	720.9	2767.8	24	114	378
Exempt middle-high income	98,832	2.3%	696.8	2777.1	17	94	334
Exempt high income	397,233	9.3%	797.9	3817.2	0	38	235
Exempt other reason	1,436,616	33.7%	501.2	2994.1	1	22	119
No. of hospitalization							
0	3,777,073	88.6%	226.3	728.4	9	61	245
1	380,626	8.9%	3768.6	5440.2	1362	2297	4272
2	71,425	1.7%	9101.3	8904.1	3974	6841	11,434
3+	33,858	0.8%	18,174.6	15,304.0	9145	14,355	22,410
No. of pharmaceutical prescription							
0	931,697	21.9%	205.5	1726.9	0	21	75

(Continues)

TABLE 2 (Continued)

	Total expenditure in 2016						
	N	% Col	Mean	S. D.	25 th perc	Median	75 th perc
1	876,850	20.6%	158.3	1244.2	0	5	28
2	326,076	7.6%	350.6	1895.8	15	34	116
3+	2,128,359	49.9%	1461.3	4313.9	115	322	904
Diagnostic cost group (DCG)							
No	3,784,039	88.8%	226.7	730.9	9	61	245
Yes	478,943	11.2%	5631.1	8194.2	1614	3033	6466
Pharmacy cost group (PCG)							
No	2,884,260	67.7%	406.0	2302.7	5	34	131
Yes	1,378,722	32.3%	1728.8	4639.1	186	446	1109

Abbreviations: DCG, Diagnostic cost group; PCG, Pharmacy cost group.

We deployed the following ML algorithms: penalized regressions (lasso, ridge, and elastic net penalties), a generalized additive model (GAM), RF, and, finally, we constructed a SL, an ensembling method that takes a weighted average of predicted values from underlying candidate algorithms (such as penalized regressions, GAMs, and RFs) to produce a single best prediction function. (M. J. van der Laan & Rose, 2011; Mark J. van der Laan et al., 2007). For further background on these methods and their application to risk adjustment we refer the interested reader to Rose (2016).

5.2 | Model performance

We randomly sampled 100,000 observations from our total sample. We divided this subset a training set (70%), to develop and validate the algorithms, and test set (30%) to evaluate the performance of the models (Appendix C reports summary statistics for the train and test sets). To choose the optimal tuning parameters of the penalized linear regressions, 10-fold cross-validation was used within the training set. For the RF, 500 trees were produced (node size = 250) and p/3 predictors, for each specification formula, were randomly chosen at each step of the tree-building.

Model fit was judged using the adjusted- R^2 and mean squared error (MSE). Predictive Ratios (PR) were computed as the ratio between mean predicted spending and mean observed spending in each observed quintile. We also calculated mean under/overcompensation, computed as the difference between mean predicted spending and the mean observed spending in each quintile. For MSE, a smaller value indicates better performance. An adjusted- R^2 a value closer to one indicates more explanatory power, while PR values between 0.9 and 1.1 are considered reasonable prediction accuracy (Kautter et al., 2012). The Relative Efficiency (RE) of each algorithm compared to OLS, with respect to both cross-validated MSE ($RE = cv\ MSE_{OLS}/cv\ MSE_k$, k = other algorithms) and R^2 values ($RE = cv\ R^2_k/cv\ R^2_{OLS}$, k = other algorithms), was evaluated. A total of 54 models were estimated to predict healthcare expenditure (based on six data scenarios and nine algorithms). Statistical analyses were performed using SAS Enterprise Guide (version 7.1) and R (version 3.6.3).

6 | RESULTS

6.1 | Evaluation of the models: Adjusted- R^2 and MSE

Tables 3 and 4 report the best and worst performing models compared to OLS according to adjusted- R^2 and MSE, respectively. In all scenarios, SL displayed the best performance, except in the coarse granularity/poor range of variables setting, in which the lasso model performed best (in both adjusted- R^2 and MSE measures). However, in this setting, the performance difference between models was trivial, such that the RE was 1 across all models. Focusing on the adjusted- R^2 , the gain in relative efficiency compared to OLS was higher in the coarse granularity/rich range of variables setting (SL adj.- R^2 = 49.9%) and in the fine granularity/poor range of variables (SL adj.- R^2 = 4.6%), but in both these settings there was no gain in RE. In the fine granularity/fair and rich range of variables scenarios, the SL RE was 1.0, with an adjusted- R^2 of 43.6% and 45.1% when DCG and DCG+PCG were added, respectively. We obtained inconsistent values (the predictions were so poor that the adjusted- R^2

TABLE 3 Adjusted-R² of the models compared to OLS

	Poor range of variables			Fair range of variables			Rich range of variables		
	Models ranking	Adj. R ²	RE	Models ranking	Adj. R ²	RE	Models ranking	Adj. R ²	RE
Coarse granularity	<i>Lasso</i>	4.3%	1.0	<i>SL</i>	48.8%	1.0	<i>SL</i>	49.9%	1.0
	<i>ElNet</i>	4.3%	1.0	<i>GAM</i>	48.0%	1.0	<i>RF</i>	49.1%	1.0
	<i>RF</i>	4.3%	1.0	<i>OLS</i>	47.6%	1.0	<i>GAM</i>	48.9%	1.0
	<i>SL</i>	4.3%	1.0	<i>Lasso</i>	47.6%	1.0	<i>OLS</i>	48.5%	1.0
	<i>GLM l-g</i>	4.3%	1.0	<i>ElNet</i>	47.6%	1.0	<i>Lasso</i>	48.5%	1.0
	<i>GLM l-n</i>	4.3%	1.0	<i>RF</i>	47.5%	1.0	<i>ElNet</i>	48.5%	1.0
	<i>OLS</i>	4.3%	1.0	<i>Ridge</i>	47.3%	1.0	<i>Ridge</i>	48.2%	1.0
	<i>GAM</i>	4.3%	1.0	<i>GLM l-n</i>	Inc. value	-	<i>GLM l-n</i>	Inc. value	-
	<i>Ridge</i>	4.3%	1.0	<i>GLM l-g</i>	Inc. value	-	<i>GLM l-g</i>	Inc. value	-
	Models ranking	Adj. R ²	RE	Models ranking	Adj. R ²	RE	Models ranking	Adj. R ²	RE
	Models ranking	Adj. R ²	RE	Models ranking	Adj. R ²	RE	Models ranking	Adj. R ²	RE
Fine granularity	<i>SL</i>	4.6%	1.0	<i>SL</i>	43.6%	1.0	<i>SL</i>	45.1%	1.0
	<i>GLM l-n</i>	4.6%	1.0	<i>GLM l-n</i>	43.2%	1.0	<i>Lasso</i>	44.9%	1.0
	<i>RF</i>	4.5%	1.0	<i>Lasso</i>	43.2%	1.0	<i>ElNet</i>	44.9%	1.0
	<i>Lasso</i>	4.5%	1.0	<i>ElNet</i>	43.2%	1.0	<i>OLS</i>	44.9%	1.0
	<i>ElNet</i>	4.5%	1.0	<i>OLS</i>	43.2%	1.0	<i>GAM</i>	44.9%	1.0
	<i>OLS</i>	4.5%	1.0	<i>GAM</i>	43.2%	1.0	<i>Ridge</i>	44.8%	1.0
	<i>GAM</i>	4.5%	1.0	<i>Ridge</i>	43.0%	1.0	<i>GLM l-n</i>	44.6%	1.0
	<i>Ridge</i>	4.5%	1.0	<i>RF</i>	42.8%	1.0	<i>RF</i>	44.5%	1.0
	<i>GLM l-g</i>	4.5%	1.0	<i>GLM l-g</i>	6.6%	0.2	<i>GLM l-g</i>	Inc. value	-

Abbreviations: GAM, generalized additive model; MSE, mean squared error; OLS, Ordinary least squares; RF, random forest; SL, super learner.

were negative and the MSEs were extremely high) for the GLMs, denoting their poor performances. The lowest adjusted-R² of OLS was 4.3% in the coarse granularity/poor range of variables data while the highest was 48.5%, obtained in the coarse granularity/rich range of variables data.

Concerning MSE, in the coarse granularity/poor range of variables and fine granularity/fair and rich range of variables scenarios, there were no gains in RE of using SL compared to OLS. ML technique produced slight gain in the coarse granularity/fair range and rich range of variables scenarios, where SL reduced the MSE by 2.1% (MSE = 5,705,097; RE = 1.02) and by 2.6% (MSE = 5,583,558; RE = 1.03). The GLMs yielded extremely high MSE values and the worst performance in many scenarios. The worst MSE of OLS was in the coarse granularity/poor range of variables data (MSE = 10,657,875) while the best was in the coarse granularity/rich range of variables data (MSE = 5,734,502).

We carried out further analyses, in which we compared the performance of the ML models, estimated on a subsample of the population as above, with that of the OLS model, estimated on the entire population of 4,262,982 individuals ("OLS total"). The results are presented in the appendix D and E. In the coarse and fine granularity/poor range of variables scenarios, OLS total outperformed the best ML algorithm for both adjusted-R² and MSE. Concerning MSE, the gap between the best ML model and the OLS total model narrows, until it reverses the sign in the fine granularity/rich range of variables scenario.

6.2 | Under/overcompensation and predictive ratios

Figure 1 shows the mean under/overcompensation by observed spending quintile. Complete tables for each data scenario of mean under/overcompensation and PRs are reported in Appendix F and G. In the coarse granularity/poor range of variables scenario all models highly overcompensate the expenditure of the individuals in the 80th percentile group (best: ridge = 822.8; worst: OLS = 826.5) as well as in the fine granularity/poor range of variables (best: SL = 859.7; worst: OLS = 868.9). In the 99th percentile all models highly undercompensate. In contrast, the 99th percentile group is (in a lesser extent) overcompensated in the fair and rich range of variables settings, for both coarse and fine granularity. Finally, in the coarse granularity/rich range of variables setting we also see the lowest under/overcompensation relative to the other scenarios for the 20th percentile.

TABLE 4 Average cross-validated MSE of the models compared to OLS

	Poor range of variables			Fair range of variables			Rich range of variables		
	Models ranking	MSE	RE	Models ranking	MSE	RE	Models ranking	MSE	RE
Coarse granularity	<i>Lasso</i>	10,657,793	1.0	<i>SL</i>	5,705,097	1.0	<i>SL</i>	5,583,558	1.0
	<i>ElNet</i>	10,657,794	1.0	<i>GAM</i>	5,791,326	1.0	<i>RF</i>	5,663,559	1.0
	<i>RF</i>	10,657,813	1.0	<i>OLS</i>	5,830,424	1.0	<i>GAM</i>	5,689,220	1.0
	<i>SL</i>	10,657,862	1.0	<i>Lasso</i>	5,830,718	1.0	<i>OLS</i>	5,734,502	1.0
	<i>OLS</i>	10,657,875	1.0	<i>ElNet</i>	5,830,867	1.0	<i>Lasso</i>	5,735,406	1.0
	<i>GAM</i>	10,657,875	1.0	<i>RF</i>	5,842,105	1.0	<i>ElNet</i>	5,735,468	1.0
	<i>GLM l-n</i>	10,657,875	1.0	<i>Ridge</i>	5,863,916	1.0	<i>Ridge</i>	5,766,763	1.0
	<i>GLM l-g</i>	10,657,875	1.0	<i>GLM l-n</i>	13,446,690	0.4	<i>GLM l-n</i>	41,287,682	0.1
	<i>Ridge</i>	10,658,065	1.0	<i>GLM l-g</i>	Inc. value	-	<i>GLM l-g</i>	Inc. value	-
	Models ranking	MSE	RE	Models ranking	MSE	RE	Models ranking	MSE	RE
Fine granularity	<i>SL</i>	10,618,384	1.0	<i>SL</i>	6,272,971	1.0	<i>SL</i>	6,100,482	1.0
	<i>GLM l-n</i>	10,620,560	1.0	<i>GLM l-n</i>	6,324,134	1.0	<i>Lasso</i>	6,130,363	1.0
	<i>RF</i>	10,629,964	1.0	<i>Lasso</i>	6,328,133	1.0	<i>ElNet</i>	6,130,485	1.0
	<i>Lasso</i>	10,632,277	1.0	<i>ElNet</i>	6,328,270	1.0	<i>OLS</i>	6,130,908	1.0
	<i>ElNet</i>	10,632,394	1.0	<i>OLS</i>	6,328,300	1.0	<i>GAM</i>	6,130,908	1.0
	<i>OLS</i>	10,632,491	1.0	<i>GAM</i>	6,328,300	1.0	<i>Ridge</i>	6,141,734	1.0
	<i>GAM</i>	10,632,491	1.0	<i>Ridge</i>	6,344,566	1.0	<i>GLM l-n</i>	6,164,559	1.0
	<i>Ridge</i>	10,632,648	1.0	<i>RF</i>	6,371,412	1.0	<i>RF</i>	6,175,096	1.0
	<i>GLM l-g</i>	10,633,779	1.0	<i>GLM l-g</i>	10,397,454	0.6	<i>GLM l-g</i>	Inc. value	-

Abbreviations: GAM, generalized additive model; MSE, mean squared error; OLS, Ordinary least squares; RF, random forest; SL, super learner.

7 | DISCUSSION

The recent developments in ML techniques to estimate healthcare spending have shown promising results, although as implemented in this study their performance is not uniformly dominant compared to OLS. The goal of this study is to provide a framework and toolkit for policymakers, therefore we selected well-established ML algorithms that required minimal tuning or could be implemented “off the shelf.” ML methods are still relatively unfamiliar for many policymakers, and some algorithms, like those based on neural networks, suffer from problems of interpretability that may limit their application (Kan et al., 2019). This study provided an in-depth analysis of the advantages and disadvantages of implementing ML techniques compared to standard regression (OLS) considering various scenarios of data granularity and range of variables and making use of healthcare administrative dataset from a large, unselected Italian population.

Our findings show that ML techniques, particularly SL, outperformed OLS in all data scenarios, although the adjusted-R² RE ranges between 0.02% points in the coarse granularity/poor range of variables scenario and 2.8% points in the coarse granularity/rich range of variables scenarios, indicating no statistically significant gain in our sample of 100,000 observations. Performance based on MSE also showed consistent results.

Concerning under/overcompensation measures, OLS showed the least, albeit negligible, overcompensation compared to ML techniques in the lowest observed spending percentiles in the coarse granularity/poor and fair range of variables setting. The top 1% spenders are better predicted with GAM or SL, except in the coarse granularity/poor range of variables and fine granularity/rich range of variables settings, where OLS was superior. The mean under/overcompensation also highlighted how the increase in the range of variables can considerably reduce the overestimation of the group of individuals in the 20th percentile and at the same time reduce the gap of the underestimation for the top of the spending distribution.

However, the gap between the best ML and OLS is relatively narrow, indicating that the implementation of more complex and sophisticated models does not lead to a significant increase in under/overcompensation reduction.

Unlike prior, US-based studies (McGuire et al., 2020; Rose, 2016), we did not find a consistent relationship between the increase in data granularity and/or range of variables and the advantage of ML over OLS. However, our most detailed data scenario (fine granularity, rich range of variables) included only 9 diagnosis-based risk adjusters, suggesting the ability of ML

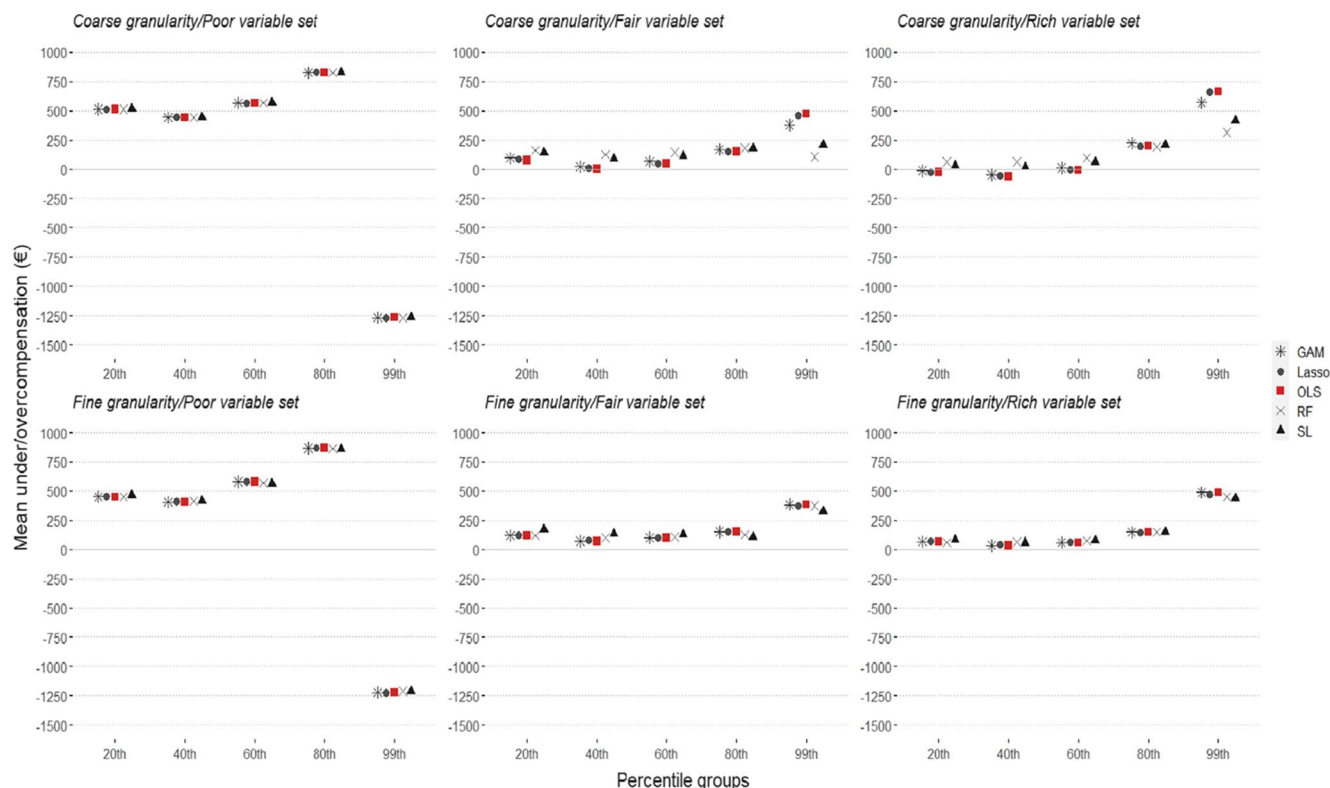


FIGURE 1 Under/overcompensation by quintiles for each data scenario. The ridge and elastic net mean compensations are not shown because they were very similar to lasso. GLMs are not shown because some of their mean compensation's values were completely out of range. Top 1% spenders were not included in the graph representation due to the higher range of values compared to quintiles (mean under compensation range from −24,971 to −14,606 €) [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/hec.4512)]

algorithms to outperform OLS with fewer variables may be limited to settings with even more granular diagnosis groupings, such as the US formulas that use 90+ diagnosis-based risk adjusters.

Increasing the range of variables produced a significant improvement in the ability of all models (excepting the GLMs) to predict healthcare expenditure, more so in the coarse than fine granularity scenarios. The jump in the adjusted- R^2 from the coarse granularity/poor range of variables to the coarse granularity/fair range of variables due the addition of the number of hospitalizations in the risk-adjustment formula is greater than the increase moving to the fine granularity/rich range of variables scenario where PCG and DCG are added. We expected this result because the number of hospitalizations is much more predictive than demographic variables and it is highly correlated with the total expenditure in the concurrent approach. However, we encourage caution regarding its use in risk-adjustment models since it may lead to inappropriate treatment decisions (Geruso & Layton, 2015). Furthermore, the underfunding of high-cost morbidities that do not require hospitalization (e.g., outpatient dialysis for chronic kidney disease patients) may still present a challenge for policymakers.

Similar to McGuire, Zink, and Rose (McGuire et al., 2020), we find the addition of pharmaceutical-based indicators (moving from fair to rich range of variables in either granularity level) does not have a large impact on the adjusted- R^2 . Although the fine granularity variables DCG and PCG reduce the adjusted- R^2 , they may be regarded as reasonable trade-offs since they generally increase efficiency and fairness, and also reduce incentives for risk selection by including more risk-classes and are better predictors in prospective approaches.

Nevertheless, in addition to the upcoding behavior that morbidity-based indicators may induce, Geruso and McGuire (Geruso & McGuire, 2016) observed that HCC-based concurrent risk-adjustment systems increase fit but at the same time they reduce the power (the term power describes the share of costs at the margin born by the health plan (Geruso & McGuire, 2016) in cost containment by about 30%, meaning that concurrent diagnosis-based risk-adjusters weaken incentives for cost control. The inclusion of pharmaceutical-based indicators in the risk-adjustment model may incentivize health care providers to prescribe unnecessary medication (van Kleef et al., 2014) but, in the long-term, PCGs may direct providers' effort to cost-containing innovations (Beck et al., 2010).

We note some specific limitations to our study. There were many alternative fine granularities diagnosis risk-adjustors that we could have selected for this comparison. We limited our choice to DCG and PCG because they are well known in the risk-adjustment literature and commonly adopted for utilization and cost outcomes. However, we believe the methods we present can guide future comparisons of other risk-adjustors. Similarly, many other ML algorithms could be compared, for example, neural networks, other decision tree-based methods, or different choices could have been made regarding the tuning parameters (Hastie et al., 2009; James et al., 2013). Ultimately, our choice of algorithms was driven by a desire for both interpretability and potential familiarity for practitioners. Concerning data sources, the OPD includes only drug dispensations that are reimbursed by the NHS. The same caveat holds for OSD. Thus, we did not capture healthcare use paid by patients either directly or funded by private insurers. Finally, we relied on combining multiple data sources to select our base population, because we lacked access to the central Resident's Registry.

The choice of the model depends crucially on the performance measures; thus, it is of foremost importance to compare various measures of fit and interpret the results very carefully. It is more appropriate to rely on the adjusted- R^2 and MSE to maximize the variance explained and reduce the overall prediction error. However, if the primary goal is to minimize the differences between the predicted values and the observed values in specific subgroups that may be at risk of selection and to incentivize cost control, then the under/overcompensation or the PR are more targeted measures.

Policymakers should consider other evaluation criteria in designing the risk-adjustment model in addition to models' predictive performance, such as time/computing power, availability of data or appropriateness for incentives for risk selection and efficiency (van Veen et al., 2015).

Generally, ML techniques – particularly the SL – out-performed OLS. From an operational perspective, we suggest implementing ML methods to increase variance explained by the model in predicting the expenditure to further decrease risk selection, to reduce upcoding actions by selecting a subset of variables over all possible covariates, and to explore possible interaction terms with automatic processes (Rose, 2016). Retaining only a small number of important variables could reduce the opportunities to inflate the number of diagnosis and facilitate care management by emphasizing key risk-factors (Kan et al., 2019; Kronick & Welch, 2014). Conversely, if algorithm performance differences on the desired evaluation metrics are considered negligible and the investment in these tools too onerous in terms of computational time, OLS may be used with large populations. In our further analyses, when the entire population is considered rather than a subsample to estimate the OLS model, we indeed observed a narrowing of the gap in the MSE measure between ML models and the OLS.

To summarize, it is well known that in designing a risk-adjustment model it is important to evaluate not only the predictive performance but also the trade-offs with adverse economic behaviors (e.g., risk selection, moral hazard, cost containment). Our analysis shows a similar trade-off when deciding between the investment in increasing the range of variables and the granularity of the data, and in the search of the more appropriate statistical techniques to implement in conjunction with a given data scenario.

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CONFLICT OF INTEREST

The authors have declared no conflict of interest.

DATA AVAILABILITY STATEMENT

The datasets generated and/or analyzed during the current study are property of a third party that is Emilia-Romagna Regional Health Agency (<https://assr.regione.emilia-romagna.it/>) and, although they are anonymized, datasets are not publicly available due to the current regulation on privacy. The description of the administrative databases is available from the website <https://salute.regione.emilia-romagna.it/siseps/sanita/asa/documentazione>. Other researchers can obtain access to the data through a formal request based on a research project to the Emilia-Romagna Regional Health Agency. We obtained the access to the data in the framework of a research agreement between the University of Bologna and the Local Health Authority of Bologna entitled “New funding mechanisms for the Italian National Health Service and the Emilia-Romagna Regional Health Service”.

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SUPPORTING INFORMATION

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