



Supplement of

Building-level exposure asset value modelling for Germany: an Ahrweiler case study

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S1 Introduction: Cost Bases explanation

Replacement costs (RC) represent the amount required to replace an asset with a new one, also defined as (re-)construction costs. These include the cost of rebuilding after a damage event, factoring in the prices of construction materials and associated expenditures. However, Daniell and Wenzel [2014] argue that *reconstruction costs* should be viewed separately as they can sometimes be higher than replacement costs due to additional laws and regulations introduced as part of the reconstruction process [Daniell and Wenzel, 2014, Daniell, 2014]. *Depreciated costs*, sometimes referred to as *actual worth* or *repair costs*, reflect the actual value of an asset at the time of assessment [Merz et al., 2010, Jongman et al., 2012, Daniell and Wenzel, 2014], representing the economic value of properties based on their pre-damage conditions [Gerl et al., 2016]. Depreciated costs are often defined as *net asset values* (NAVs), which are usually derived from national accounting systems where fixed asset stocks are recorded. In Germany, these calculations adhere to the *perpetual inventory method* (PIM) [Schmalwasser and Schidlowski, 2006], where the stock of fixed assets is determined by annually documenting incoming and outgoing assets. In this framework, *gross fixed assets* encompass all produced assets that are utilised repeatedly or continuously in production processes for over a year, without accounting for depreciation. These include both tangible and intangible assets. Tangible fixed assets cover machinery, equipment, residential and non-residential buildings, and cultivated assets. Intangible fixed assets include mineral exploration, computer software, large databases, and original works such as entertainment, literary, or artistic creations [Schmalwasser and Schidlowski, 2006]. For *net fixed assets*, a depreciation rate is applied to account for the reduction in value over time, considering the average lifespan of the asset which is defined by many factors such as the quality of construction or the durability of building materials. While net asset values are considered for depreciated costs, gross asset values are often used for replacement/reconstruction costs [Schmalwasser and Schidlowski, 2006].

In other countries, slightly differing concepts exist where assets are quantified by the *Gross/Net Capital Stock* of a country including the *Gross Fixed Capital Formation* [Daniell and Wenzel, 2014, Daniell, 2014]. A detailed differentiation of these concepts is out of scope of the present work; however, explanations can be found in [Schmalwasser and Schidlowski, 2006]. Market value refers to the price at which a building can be traded in the marketplace at the time of evaluation, reflecting the cost of purchasing rather than reconstructing a building. Lastly, Insured Value is the value assigned to a building for the purpose of insurance, determined by the risk portfolio of the respective insurance company, which usually apply the gross concept instead of the net concept [Daniell, 2014, p.70].

S2 Methods: Systematic search for exposure datasets on building assets

A systematic search was conducted for freely available exposure data on building locations and building assets in Europe and Germany (with the exception of the BKI dataset which requires purchasing). A range of relevant search terms was employed, and searched for in several search engines, presented in Table S1. Additionally, the website of the “Federal Agency for Cartography and Geodesy” (*Bundesamt für Kartographie und Geodäsie*, translated) [BKG, 2025] was searched for suitable datasets.

The results were reviewed and datasets were selected according to the following criteria. Datasets had to be freely accessible, cover the full national extent of Germany, and provide at least one of the following: *building location*; *building size*; *building use type*; *building asset values*. Regionalised or disaggregated asset values were preferred over aggregated national values. Table S2 lists the datasets considered, indicates which were selected, and provides the selection justifications.

Table S1: Search engines and search terms applied in systematic search for exposure datasets on building assets

search engine	search terms
Google & Google Scholar & BKG website	“building asset value data Germany”; “building asset datasets Germany”; “flood risk map Germany”; “flood exposure datasets Germany”; “exposure datasets Europe”; “flood exposure Europe datasets”; “European flood risk database”; “exposure datasets for natural disasters assessment”; “european earthquake damage exposure models”; “exposure models for natural disasters assessment”; “3D building data Germany”; “building location data Germany”; “land use datasets”; “free land use data”
references:	Google [2025a] & Google [2025b] & BKG [2025]

Table S2: List of datasets considered including those selected, and justifications for the selection

dataset	reference	selected	justification
Eurostat GVA Regional	Eurostat [2025b]	yes	provides regional economic output by NUTS 3 region and sector group, used to distribute national capital stocks to the study region
Eurostat Stocks	Eurostat [2025a]	yes	provides national fixed-asset values by economic sector and detailed asset type, used as the basis for non-residential Eurostat asset values
Insee Capital Stocks	Insee [2022]	yes	provides gross fixed-capital ratios used to disaggregate Eurostat <i>Other buildings and structures</i> values to <i>Buildings other than dwellings</i>
Paprotny [2022]	Paprotny [2022]	yes	provides residential replacement-cost values per floor area for dwellings and household contents, used for the residential component of LoD1+Eurostat
BEAM	Copernicus [2020]	yes	provides building assets already classified in economic sectors and disaggregated to land-use polygons
EHRE	Nievas et al. [2023]	yes	provides asset values mapped onto OBM building features, classified into occupancy cases and structural types
LoD1	BKG [2023]	yes	provides building location, footprint area, height, and use type; covers national extent; and is produced by a federal agency
OSM	OpenStreetMap contributors [2017]	yes	provides 35 land-use types suitable for classifying buildings into economic sectors at national to international scale
CORINE	Copernicus [2018]	yes	provides seamless land-use coverage, used where OSM land-use polygons were unavailable
NUTS-regions	BKG [2024b]	yes	provides the NUTS regional boundaries needed to join regional tabular asset values to the study area
BKI book	BKI [2021]	yes	provides building-type-specific construction costs and regionalisation factors used for the benchmark asset values
OSM buildings	OpenStreetMap contributors [2017]	no	provides building footprints, but LoD1 was preferred because it includes official building height and function attributes
Destatis	Destatis [2025]	no	provides German national accounts data, but equivalent values were accessed through Eurostat for consistency with the regional workflow
ESRM20	Crowley et al. [2021, 2020]	no	spatially aggregated; its data are embedded into EHRE, which maps them onto individual buildings
ALKIS	AdV [2023]	no	not selected because the available product did not provide building height for the required geometry-based valuation
LBM-DE2018	BKG [2024a]	no	not selected because access was more restrictive than the alternative land-use datasets

S3 Methods: Asset Value Model Workflows

S3.1 LoD1+Eurostat

Table S3: Statistical Classification of Economic Activities in the European Community (NACE) Rev. 2 economic sector groups [European Commission, 2008] provided in Eurostat [2025b].

sector group	NACE code	section title
agriculture	A	Agriculture, forestry and fishing
production	B	Mining and quarrying
	C	Manufacturing
	D	Electricity, gas, steam and air conditioning supply
	E	Water supply; sewerage, waste management and remediation activities
construction	F	Construction
market services	G	Wholesale and retail trade; repair of motor vehicles and motorcycles
	H	Transportation and storage
	I	Accommodation and food service activities
	J	Information and communication
corporate services	K	Financial and insurance activities
	L	Real estate activities
	M	Professional, scientific and technical activities
	N	Administrative and support service activities
non-market services	O	Public administration and defence; compulsory social security
	P	Education
	Q	Human health and social work activities
	R	Arts, entertainment and recreation
	S	Other service activities
	T	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
	U	Activities of extraterritorial organizations and bodies

Table S4: Asset classification subcategories of “Other buildings and structures” (AN.112) from Eurostat [2013]

Classification of assets	Short description	Examples
Buildings other than dwellings (AN.1121)	Non-residential buildings, including integral fixtures and site preparation; includes public monuments identified primarily as non-residential buildings.	“warehouse and industrial buildings, commercial buildings, buildings for public entertainment, hotels, restaurants, educational buildings, health buildings”
Other structures (AN.1122)	Structures other than residential ones; includes streets, sewers, site preparation, certain public monuments, mining works, and coastal protection works improving adjacent land.	“highways, streets, roads, railways and airfield runways; bridges, elevated highways, tunnels and subways; waterways, harbours, dams... long-distance pipelines, communication and power lines... constructions for mining... and for sport and recreation”
Land improvements (AN.1123)	Actions that improve the quantity, quality or productivity of land, or prevent its deterioration; also includes not-yet-written-off land transfer costs.	“land clearance, land contouring, creation of wells and watering holes”

Table S5: Eurostat and Insee derived national building replacement values for 2018 from Eq. 1. Note these are aggregated to the six sectors shown in Table S6 in a later step.

NACE code(s)	$RC_{n,AN.112}$ [€]	$\frac{GFC_{AN.1121}}{GFC_{AN.112}}$
A	2.40×10^{11}	1.00
B-E	1.22×10^{12}	0.59
F	5.51×10^{10}	0.40
G-I	9.90×10^{11}	0.44
J	1.52×10^{11}	0.31
K	2.94×10^{11}	1.00
L	7.35×10^{11}	0.23
M-N	2.08×10^{11}	0.50
R-U	3.90×10^{11}	0.62
O-Q	2.42×10^{12}	0.34

Table S6: Eurostat derived national and NUTS-3 regional (Ahrweiler [DEB12]) values for 2018 from Eq. 1. See Table S5 for additional values.

sector	NACE code(s)	$GV A_r / GV A_n$	$RC_{r,AN.1121}$ [€]
agriculture	A	1.40×10^{-3}	3.36×10^8
production	B-E	7.76×10^{-4}	5.53×10^8
construction	F	1.40×10^{-3}	3.11×10^7
market services	G-J	1.00×10^{-3}	4.90×10^8
corporate services	K-N	9.64×10^{-4}	5.48×10^8
non-market services	O-U	1.28×10^{-3}	1.35×10^9

Sector	Total	Equipment	Buildings
Total	100.00%	15.31%	84.69%
Agriculture, forestry and fishing	1.71%	51.06%	48.94%
Manufacturing industry	12.18%	58.36%	43.64%
Service sectors	86.11%	8.80%	91.20%

Table S7: Proportions used to differentiate asset values into building and equipment assets from national accounting of fixed assets provided by the federal statistical offices of Germany [Arbeitskreis Volkswirtschaftliche Gesamtrechnungen der Länder, 2023]. Values correspond to the federal state of Rhineland-Palatinate based on the year 2018. Total column shows the shares of the respective sector compared to the total assets in the state of Rhineland-Palatinate.

S3.3 EHRE

Table S8: Reconstruction costs and replacement-cost composition by asset class in Germany from Crowley et al. [2021]

Asset class	Subcategory	Reconstruction cost (EUR m ⁻²)	Replacement-cost composition (%)		
			Structural	Non-structural	Contents
residential	Rural areas	1300			
	Urban areas	1700	30	50	20
	Big cities	1900			
commercial	Offices	1600			
	Wholesale & retail trade	1200	20	30	50
	Hotels & restaurants	1680			
industrial	General facilities	800	15	25	60

The adjustment factors for different construction materials are the same for all occupancy cases, and are as follows:

- Unreinforced masonry, adobe blocks, wood: 0.95
- Reinforced concrete, masonry with unknown reinforcement: 1.05
- Steel, mixed materials (hybrid or composite), other: 1.00

S4 Methods: Benchmark dataset

The most challenging characteristic was the presence of basements in case of detached and semi-detached buildings, as this was often not possible to determine solely by inspecting the building from the outside. In many cases, however, small windows on the ground level could be observed which proved the presence of a basement. In all other cases, no basement was assumed, and an additional column was introduced to the data indicating the uncertainty of whether a basement exists or not.

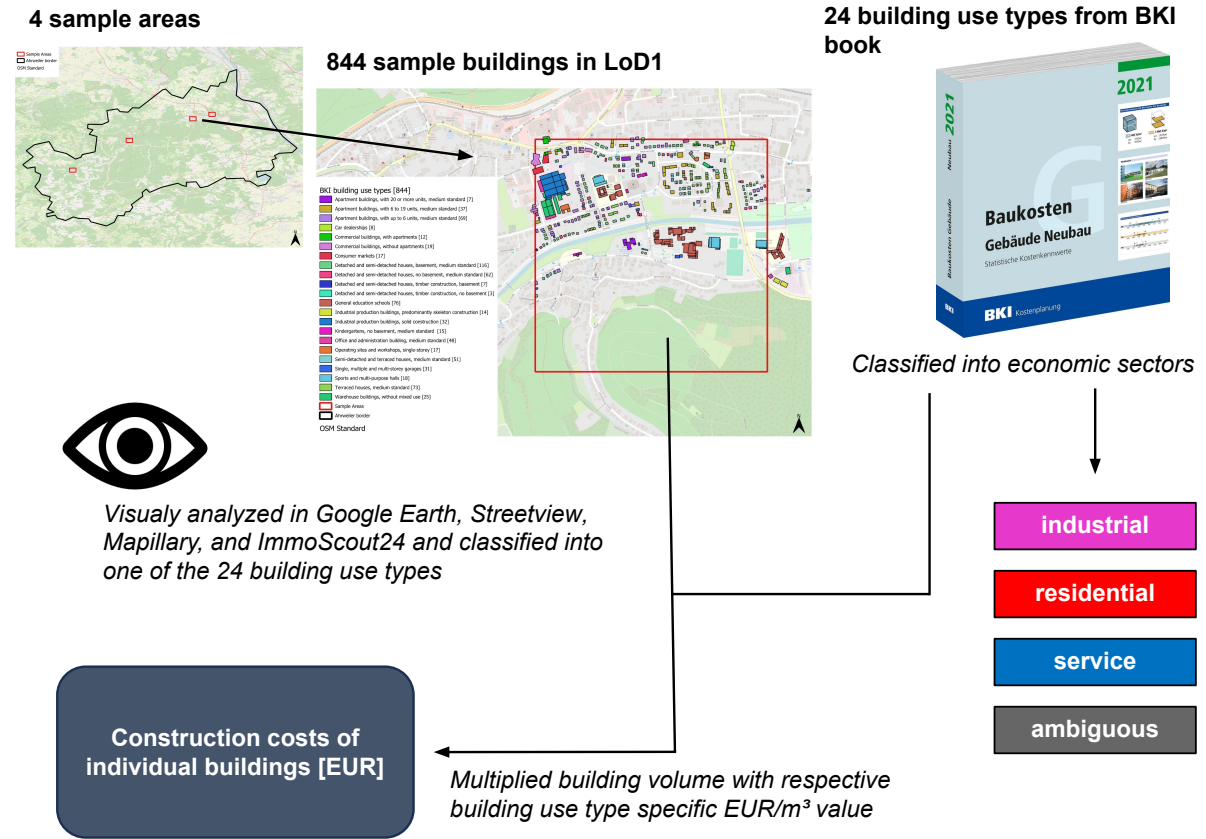


Figure S1: Benchmark dataset creation. See main text for details. © OpenStreetMap contributors 2025. Distributed under the Open Data Commons Open Database License (ODbL) v1.0. Image source: BKI [2021].

Table S9: New-building unit construction costs for 2021 from BKI [2021]. Unit costs were collected from chapters corresponding to the relevant building types. €/m³ values refer to *Bruttorauminhalt (BRI; gross volume)*, the volume enclosed by the foundation, exterior walls, and roof. The book also reports €/m² values for *Bruttogrundfläche (BGF; gross floor area)* and *Nutzungsfläche (NUF; usable floor space)*, but these were not applied in this analysis [Zschiesche, 2021]. Unit costs presented here were later adjusted for Ahrweiler county by applying a regionalisation factor of 0.986 provided in BKI [2021].

BKI sector	BKI building type	BKI unit costs (EUR/m ³)
ambiguous	Commercial buildings, with apartments	495
ambiguous	Warehouse/storage building, single-use	160
ambiguous	Single, multiple and multi-storey garages	165
industrial	industrial production buildings, solid construction	250
industrial	industrial production buildings, predominantly skeleton construction	210
industrial	Operating sites and workshops, single-storey	290
residential	Detached and semi-detached houses, basement, medium standard	445
residential	Detached and semi-detached houses, no basement, medium standard	455
residential	Detached and semi-detached houses, timber construction, basement	470
residential	Detached and semi-detached houses, timber construction, no basement	495
residential	Semi-detached and terraced houses, medium standard	425
residential	Terraced houses, medium standard	370
residential	Apartment buildings, with up to 6 units, medium standard	440
residential	Apartment buildings, with 6 to 19 units, medium standard	425
residential	Apartment buildings, with 20 or more units, medium standard	410
service	Office and administration building, medium standard	495
service	General education schools	445
service	Commercial buildings, without apartments	495
service	Consumer markets	215
service	Kindergartens, no basement, medium standard	490
service	Car dealerships	315
service	Sports and multi-purpose halls	345
service	Medical facilities	545
service	Nursing homes	510

S5 Results: Classification Comparison

We evaluated sector classification using a one-vs-rest confusion framework. For this, we first addressed spatial joining of EHRE against the benchmark dataset (the other workflows already shared the same spatial reference as the benchmark dataset, so no spatial joining was necessary) as shown in Figure S2, which illustrates the following scenarios:

- **a**: simple 1:1 match.
- **b**: spatial mismatch between the benchmark dataset and EHRE. The features existed only in the benchmark (LoD1) but not in EHRE (OSM); therefore, these orphaned benchmark dataset features could not be compared against EHRE.
- **c**: spatial join necessary. These features were considered as one single-part building in EHRE (OSM), but as multi-part building blocks in the benchmark (LoD1). Therefore, the benchmark dataset buildings had to be spatially merged by hand. This is the reason why the benchmark dataset building count for EHRE is lower.
- **d**: ignored features. These features existed only in EHRE and were therefore excluded from the analysis.
- **e**: out of domain (OOD): features outside the evaluated EHRE/ESRM20 sector labels. These features existed in the benchmark (LoD1) and in EHRE (OSM). However, in EHRE these were labelled as “other” which did not match any label in the benchmark dataset. These were retained and treated as abstentions: they were counted as false negatives for the corresponding true class and were not assigned as false positives to any evaluated class.

The following label equivalency is assumed for the classification evaluation metrics:

Table S10: Classification label equivalency for per-label performance metrics from Fig. 7. OOD: out-of-domain

workflow	label	benchmark dataset label
EHRE	commercial	service
EHRE	other	OOD
Eurostat	non-market services	service
Eurostat	market services	service
Eurostat	corporate services	service
OSM land-use	agricultural	OOD

For the Weighted Scoring Model, we converted these benchmark dataset classification metrics to a 0–10 score by multiplying the mean of precision, recall, and F_1 by 10 and rounding to the nearest integer.



Figure S2: Examples of spatial mismatches between EHRE and the benchmark dataset.

Table S11: Per-label performance of sector classification model workflows from Fig. 7. See Table S10 for label mapping. This is the main reported parameterisation: EHRE “mismatched” assets are excluded while out-of-domain (OOD) predictions are retained for the metric calculations.

workflow	benchmark sector	TP	FP	FN	TN	OOD	precision	recall	F1
LoD1+EUROSTAT (panel a)	Residential	414	62	8	360	0	0.87	0.981	0.922
LoD1+EUROSTAT (panel a)	Service	240	128	48	428	0	0.652	0.833	0.732
LoD1+EUROSTAT (panel a)	Industrial	0	0	66	778	0	0.0	0.0	0.0
LoD1+EUROSTAT (panel a)	Ambiguous	0	0	68	776	0	0.0	0.0	0.0
LoD1+BEAM (panel b)	Residential	414	62	8	360	0	0.87	0.981	0.922
LoD1+BEAM (panel b)	Service	240	128	48	428	0	0.652	0.833	0.732
LoD1+BEAM (panel b)	Industrial	0	0	66	778	0	0.0	0.0	0.0
LoD1+BEAM (panel b)	Ambiguous	0	0	68	776	0	0.0	0.0	0.0
EHRE (panel c)	Residential	325	72	5	215	174	0.819	0.985	0.894
EHRE (panel c)	Service	3	9	212	393	174	0.25	0.014	0.026
EHRE (panel c)	Industrial	24	10	9	574	174	0.706	0.727	0.716
EHRE (panel c)	Ambiguous	0	0	39	578	174	0.0	0.0	0.0
OSM land-use (panel d)	Residential	417	319	5	103	2	0.567	0.988	0.72
OSM land-use (panel d)	Service	17	18	271	538	2	0.486	0.059	0.105
OSM land-use (panel d)	Industrial	47	24	19	754	2	0.662	0.712	0.686
OSM land-use (panel d)	Ambiguous	0	0	68	776	2	0.0	0.0	0.0

Table S12: Performance of sector classification model workflows weighted by the benchmark dataset counts per sector from Fig. 7. See Table S10 for label mapping. This table uses the main reported parameterisation described in Table S11.

workflow	precision	recall	F1
LoD1+EUROSTAT (panel a)	0.657	0.775	0.711
LoD1+BEAM (panel b)	0.657	0.775	0.711
EHRE (panel c)	0.563	0.57	0.526
OSM land-use (panel d)	0.501	0.57	0.45

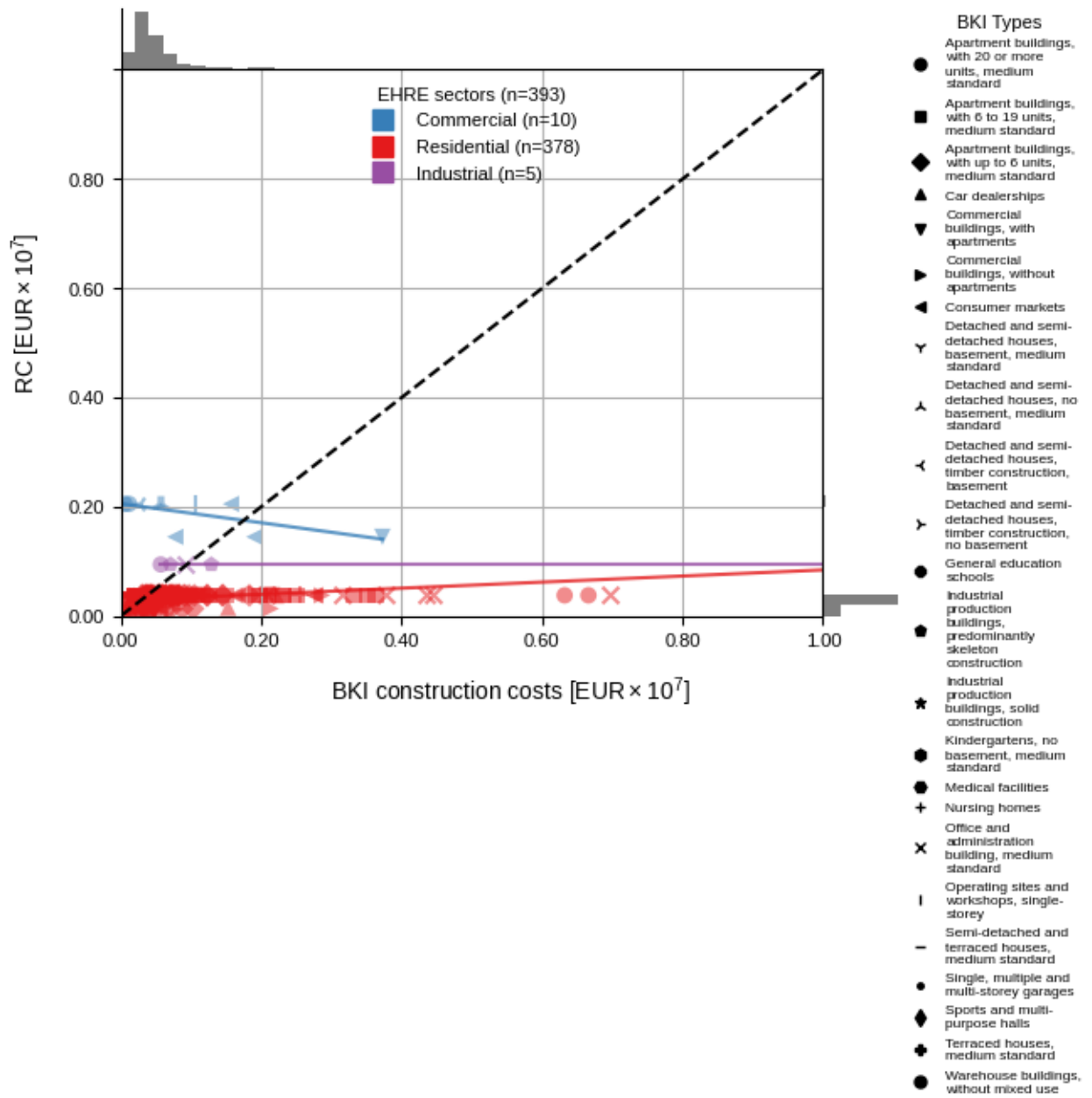


Figure S3: Asset values for the EHRE based asset value model in the four sample areas (Figure 1) against the benchmark BKI [2021] dataset. Data markers represent the BKI [2021] type and colours the EHRE sector. Solid lines provide the linear trend of the respective sector while the dashed line shows 1:1 perfect agreement. Distributions of respective asset values are shown as histograms adjacent to the axes.

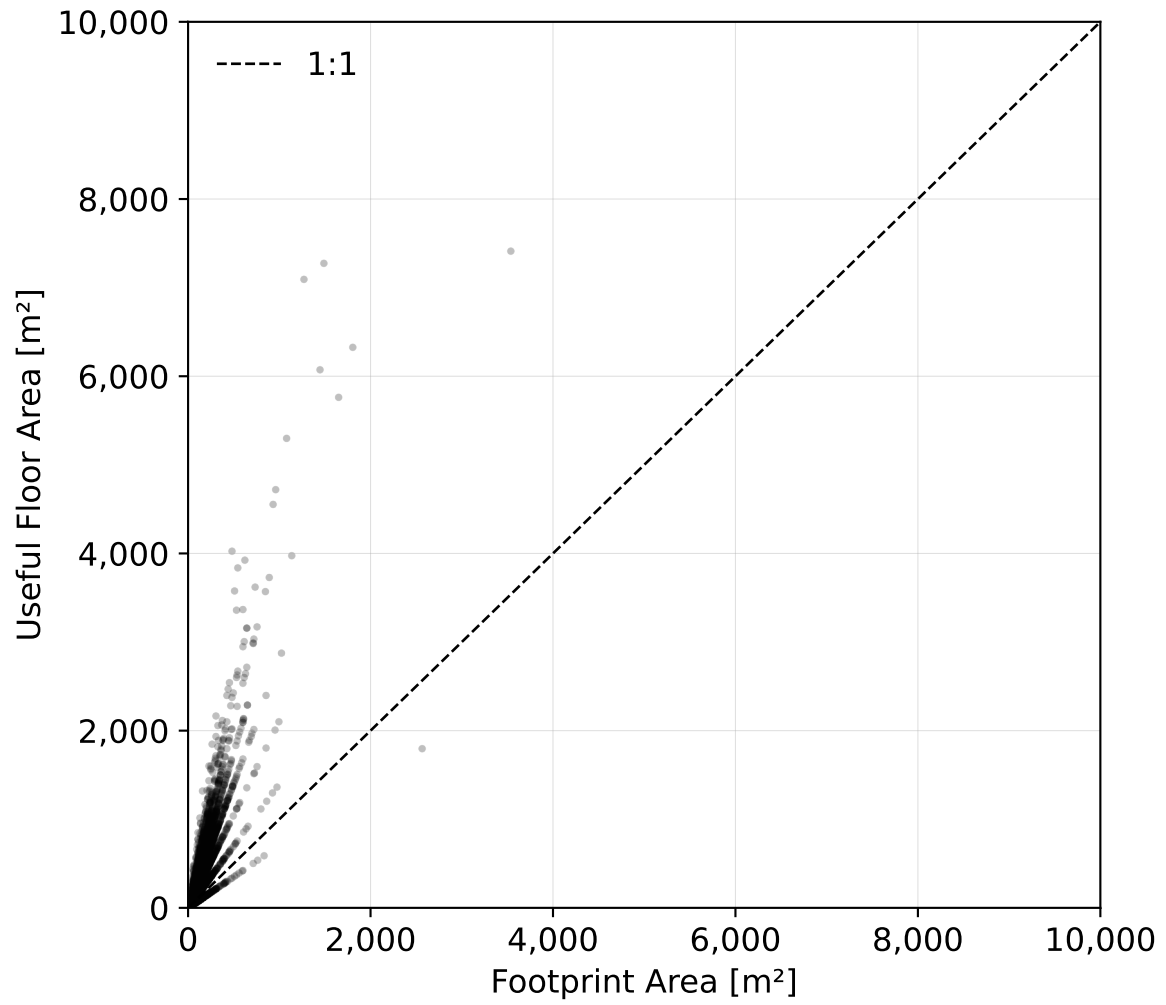


Figure S4: Relationship between building footprint area and usable floor area for residential buildings in Ahrweiler.

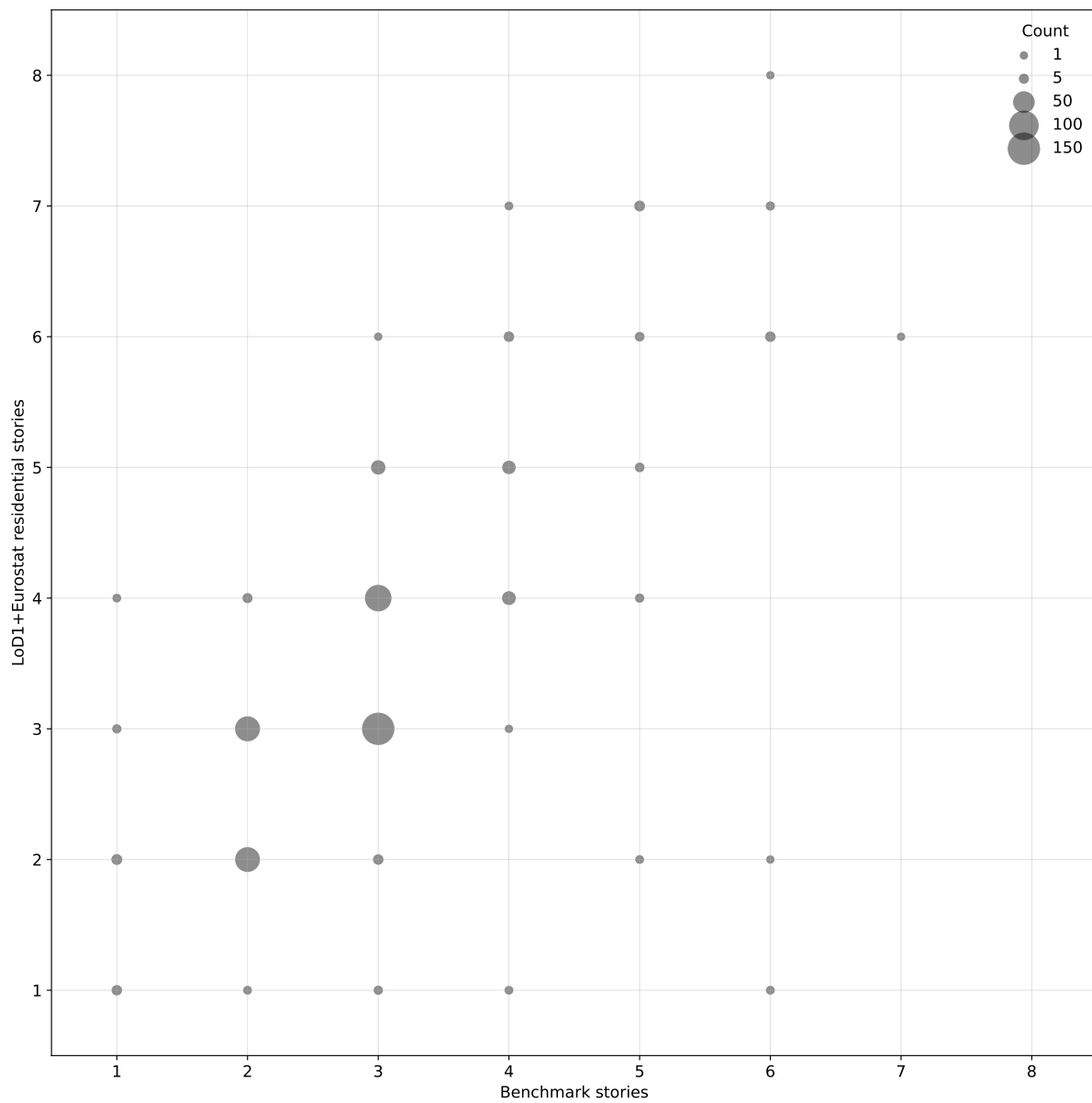


Figure S5: Comparison of storeys observed visually in the benchmark dataset and storeys calculated in the LoD1+Eurostat workflow.

S7 Results: Weighted Scoring Model

Table S13: Criteria for Weighted Scoring Model evaluation of asset value model workflows.

Criteria	Description
Benchmark classification	Rates the performance of the workflow at matching the classification of the benchmark dataset. Higher conformity with the benchmark dataset results in higher scores.
Benchmark values	Rates the performance of the workflow at matching the per-asset values of the benchmark dataset. Closer alignment with the benchmark dataset results in higher scores.
Sustainability	Rates the barriers to access (e.g., license restrictions, data hosting) and frequency of updates of the underlying data. Easier access and more frequent updates result in higher scores.
Model parsimony	Rates the complexity required to construct the exposure model workflow from the source data. Simpler, more parsimonious workflows receive higher scores.
Transparency	Rates the level of detail to which the source data pipeline is traceable and comprehensible, such as through the availability of code. Greater transparency results in higher scores.
Uncertainty handling	Rates how the workflow measures, quantifies, and communicates uncertainty. Higher scores relate to more robust uncertainty handling.
Breadth of asset types	Rates the relative breadth of asset value type data (e.g., building replacement, stocks in trade, household contents). Greater breadth results in higher scores.
Adaptability	Rates the ability of the workflow to adapt to specific regions and times. Greater adaptability yields higher scores.

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