A structural catalogue of the settlement morphology in refugee and IDP camps

Matthias Weigand[a] and Simon Worbis[a,b] and Marta Sapena[a] and Hannes Taubenböck[a,c]

[a]German Aerospace Center (DLR), German Remote Sensing Data Center (DFD), Wessling, Germany;
[b]Munich University of Applied Sciences, Department of Geoinformatics, Munich, Germany;
[c]Julius-Maximilans-Universität Würzburg, Department for Geography and Geology, Würzburg, Germany

ARTICLE HISTORY
Compiled February 2, 2024

Abstract
In the past decade, the number of refugees and internally displaced people (IDP) has doubled. This prompted the construction of more refugee camps and the proliferation of existing camps with diverse structural morphologies. Satellite imagery and machine learning (ML) are increasingly utilized to map these camps. However, there exists no standardized inventory that systemizes the built-up structures of these camps. In this study, we conceptualize the settlement morphology of refugee and IDP camps from satellite images and create a structure catalogue. Using visual image interpretation (VII) of very-high-resolution and multitemporal imagery, we compile a global database of settlement structures from 285 camps across 1,053 observations. This catalogue is subsequently used to synthesize patterns in camp structures and temporal dynamics. The results show stark variations in settlement structures across camps. Despite some similar regional patterns, stark differences in morphologies are a testament to the global heterogeneous landscape of refugee and IDP camp structures. These findings highlight the importance of considering morphological differences in image analyses across camps in future designs of ML-based automated detection and monitoring efforts. Therein, the Structure Catalogue serves as an important foundation for future earth observation for humanitarian applications.

KEYWORDS
Refugee Camps; IDP Camps; UNHCR; Settlement Structures; Satellite Images; Earth Observation;

1. Introduction

In 2020, the number of refugees worldwide reached unprecedented levels. Over 82 million people were registered as forcibly displaced from their homes, more than doubling their numbers over the past decade (UNHCR, 2021b). Reports in 2021 even indicate a further increase to over 89 million (McAuliffe and Triandafyllidou, 2021), a trend that will continue with, e.g, climate change drastically altering the human habitat in West Africa (Interna-

This is an Accepted Manuscript of an article published by Taylor & Francis in the International Journal of Geographical Information Science on 27 Mar 2023, available at https://doi.org/10.1080/13658816.2023.2189724
CONTACT M. Weigand. Email: matthias.weigand@dlr.de

tional Organization for Migration, 2021). One physical manifestation of these devastating humanitarian crises are camps for refugee and internally displaced people (IDP) camps, many of which host thousands of people. They find a bare minimum of shelter in tents, containers, or plain huts. The camps are often initially planned as temporary solutions, but over time evolve into permanent places of residence, failing to provide any glimpse of perspective or legal status for their inhabitants (Ramadan, 2012; Kraff *et al.*, 2022).

People around the world are flocking to ever larger, ever more complex settlements. A trend that can be seen for formal cities (Taubenböck *et al.*, 2019), is also true for refugee and IDP camps around the world. With evermore people on the run, these settlements become more important places of residence. Yet, reliable spatio-quantitative data about these settlements are in demand but scarce. For example, the population density as well as the spatial layout of camps has shown to play an important role in the spreading of diseases. Recent efforts to model the spread of COVID-19 in the Cox's Bazar refugee camp in Bangladesh included information about the spatial setup and infrastructure in the camp (Aylett-Bullock *et al.*, 2021). Such efforts highlight the need for highly detailed geographical data on refugee and IDP settlements.

In areas of violent conflict or with restricted access to international and independent parties, remote sensing is typically the only tool to acquire independent, objective and large-scale spatial information about the conditions on ground. This includes settlement extents, population estimates and, with high resolution imagery available, dwelling types (Witmer, 2015, for an overview). Earth observation data has been used to describe, derive, and map settlement morphology in complex urban settings (e.g. Kuffer *et al.*, 2014; Taubenböck and Kraff, 2014; Wurm *et al.*, 2017; Georganos *et al.*, 2021). Recent approaches increasingly utilize machine learning (ML) of remote sensing imagery to provide large-scale information on the extent of fast-growing informal settlements and refugee camps (e.g. Aravena Pelizari *et al.*, 2018; Braun *et al.*, 2019; Wurm *et al.*, 2019). In addition to mapping the spatial extent of refugee camps, multi-temporal earth observation data can be used to derive information like population counts and dynamics (Lang *et al.*, 2010), supporting decision-making and guidance for humanitarian aid (Lang *et al.*, 2019). With the recent launches of high resolution space-borne sensors, like Sentinel-2, evermore data is available to be used for highly detailed land cover analyses (e.g. Weigand *et al.*, 2020).

Despite recent technological and methodological advances in image analysis, however, high quality and large quantity reference data availability remains a major challenge for developing reliable automatic mapping applications for humanitarian aid (Quinn *et al.*, 2018; Nasir *et al.*, 2022). In fact, aside from a target variable that is complex and of varying structural appearance across the globe, the challenge of deriving reliable information about refugee camps worldwide is increased by parameters like heterogeneous landscapes or differences in soil and vegetation cover (Witmer, 2015).

As a consequence, existing satellite-based settlement datasets have been shown to misrepresent refugee settlements (Van Den Hoek and Friedrich, 2021). This obscures the spatial representation of displaced people in global geographic human settlement datasets, which is why recent efforts for creating reference data explicitly include refugee and IDP camps (e.g. the WorldStrat Dataset Cornebise *et al.*, 2022). Also, initiatives like Missing Maps[1] play an important role in closing existing data gaps. The morphological diversity of camps and their potential ambiguity to formal settlements are challenging for modern ML-based techniques, as recent studies on mapping informal settlements show (Aravena Pelizari *et al.*, 2018; Stark *et al.*, 2020). Beyond that, efforts of mapping urban areas do not allow for a detailed inventory of different settlement morphologies in refugee and IDP camps as such

[1] https://www.missingmaps.org/

information is missing on a global scale. This complicates assessing the quality of previous and future mapping efforts (Wang *et al.*, 2022).

In this study, we conceptualize the different morphological structures in refugee and IDP camps across the planet. While there are detailed procedures on how to plan and build settlements, most notably the Sphere Handbook (Sphere Assotication, 2018), existing camps vary drastically in their spatial layout. We document the camp morphologies found in refugee and IDP camps using spatial-quantitative measures. From this, we compile a consistent systematization: the Structure Catalogue (SC) of refugee and IDP camp settlement morphologies. We apply visual image interpretation (VII) in a large-scale assessment of hundreds of camps. We then evaluate the reliability of VII for creating the SC using high resolution geographic reference data. Eventually, the SC is used to analyse the different complexity and dynamics of refugee and IDP camp structures worldwide. The main questions of this study are:

(1) What are distinctive features of the morphological structures in IDP and refugee camps?
(2) Is VII a reliable method to derive structure information in refugee and IDP camps?
(3) How diverse are morphological settlement structures in refugee and IDP camps across the globe?
(4) Are there geographic patterns in the distribution of certain camp morphology types across regional or continental scales?
(5) How do structural morphologies in refugee and IDP camps change over time?

To answer these questions, we first conceptualize the various aspects that allow the description of camp morphology in section 2. We outline the data and methods used in this study in section 3. Using a standardized set of morphological features, we compile the SC from hundreds of refugee and IDP camps worldwide. Further, the resulting SC is evaluated against reference data before serving as a database for a large-scale analysis of camp settlement structures. To aid interpretability of the geographic patterns, the morphological features are aggregated by compactness and geometric arrangement. The results are presented in section 4 and discussed in 5 before we conclude this study in section 6.

2. Conceptualizing refugee camp morphologies – the Structure Catalogue

2.1. *Refugee camp structures*

The spatial layout of refugee and IDP camps varies. This is reflected in satellite imagery, from strictly planned adherence to geometric patterns to more informal layouts without clear spatial planning guidelines. Leading humanitarian agencies and organizations set minimum standards on camp planning and structure[2]. For example, the Sphere standard defines minimum distances between tents or shelters to provide safety, e.g., as fire breaks (Sphere Assotication, 2018). It has been recognized that, especially in densely populated camps, hazards, such as fire, pose a significant risk to the residents (Inter-Agency Shelter Sector Corrdination Working Group, 2018). However, the defined minimum standards do not lead to more or less homogeneous settlement structures with local adaptation, but their appearance varies drastically across the globe. Some follow clear and regular patterns with rows of tents or containers planned and built from scratch. Others grow organically in previously unsettled areas or in yet uninhabited areas in cities. This variability can be attributed to

[2] https://emergency.unhcr.org/entry/35943/site-planning-for-camps

many factors, such as camp management, building materials, topography, spontaneity and history of the settlement.

Furthermore, the structures in camps are not static, but sometimes change significantly over time. The camp Cevdetiye, Turkey, located along one of the most active migration routes in 2020 from the Syrian Arab Republic to Turkey (McAuliffe *et al.*, 2021; Unite Nations Department of Economic and Social Affairs (UN DESA), 2020), allows illustrating these dynamics. It was initially built with tents and later upgraded to a village of accommodation containers (see fig. 1). Satellite data allow detecting the time of settlement formation, the structural changes over time and possibly the time of their destruction.

Figure 1. The camp Cevdetiye, Turkey in 2014 and 2018 (top) and corresponding satellite imagery (bottom). Between the two time steps, the camp was rebuilt from tents to containers. Image source satellite imagery © Google Earth, Maxar Technologies 2021 & CNES Airbus 2021; Image sources top left: © European Union 2016 - Source : EP / Photographer: Yasin Akgül; top right: © Deniz Kurt Insaat.

A systematization of these structures is still pending. Thus, we aim (1) to document the variety of camp structures around the globe in a structure catalogue. Through the multitemporal nature of satellite image time series data, it is even possible to capture the spatial dynamics (Tomaszewski *et al.*, 2016) of camps over the years. And we aim (2) to build a detailed spatial knowledge base that will allow for the creation of automated ML applications based on modern satellite data.

2.2. *Compilation of relevant morphological features – The Structure Catalogue*

Previous studies on the classification of morphologic settlement structures utilized landscape metrics based on VHR building footprint data (e.g. Jochem and Tatem, 2021; Jochem *et al.*, 2021). While they provide detailed localized morphologic abstractions, their reliance on high resolution building footprint data poses a limitation as such data are rare, and mapping errors of building footprints can introduce uncertainties for morphology evaluations (Wang *et al.*, 2022). In this study, we show that VII can alleviate some of these limitations in regions without high resolution building data. In a previous study, Taubenböck *et al.* (2018) used different morphological parameters to formalize informal and complex settlement structures of slums. Slums share many structural elements with refugee camps, e.g., a lack of formal infrastructure, predominantly single storey shelters, or high population densities. Here, we adapt this approach to the analysis of refugee and IDP camp morphology. We derive a set of morphological features specifically designed to represent the unique descriptive properties of camp structures in satellite images. Thereby, we do not imply any legal status, genesis, ethnic background, or administrative or organizational structures in the camps. These observations are descriptive and do not consider the defining reasons such as planning specifications, topography, or available building material. Thus, we aim to provide an objective, reliable description of the physical camp appearance. The features are compiled into a comprehensive database, the SC. Each camp is represented as one or multiple observations over time. Each observation records the settlement structure using the following parameters.

In general, settlement structure can be described at different scopes. We focus on three: (*a*) the building level, (*b*) the block level, and (*c*) the camp level. On the building level, the entity of analysis is individual dwellings. Blocks are defined as a closed conglomerate of dwellings with consistent or similar structural patterns. Blocks are usually separated by major paths or roads, water bodies or open spaces, all of which are not part of the blocks themselves. On the camp level, the reference unit is the entire context of the site. Table 1 summarizes the definitions of the hierarchical morphological features, figure 2 depicts them.

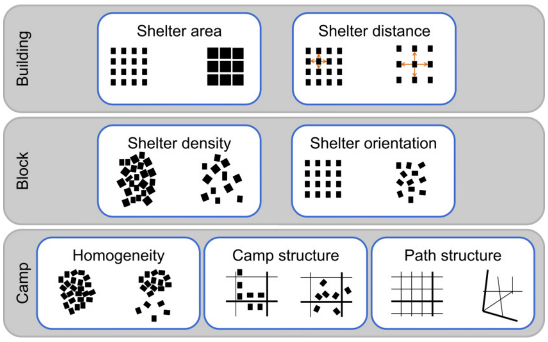

Figure 2. Conceptual visualization of seven morphological features across three hierarchical scopes of a camp captured by the Structure Catalogue.

At the building level, the size of the tents or shelters is a defining characteristic. In our approach, we define *shelter area (AREA)* as the most dominant size of the shelters in the camp. Based on observations, we distinguish between three classes: In camps categorized by small shelters, on average, *AREA* does not exceed 20 m^2. This roughly aligns with the UNHCR's family tents. Similarly, with medium-sized shelters, average shelter size does not exceed 40 m^2, and camps with large shelter area have an *AREA* of more than 40 m^2. Second, the *shelter distance (DIST)* is defined as the ratio of the distance between shelters to the shelter's axis. A ratio of 1 means, for example, that shelters with an axis of 5 metres have an average distance to the next shelter of 5 metres. A small *DIST* is defined with a ratio below 0.5, medium *DIST* is up to a ratio of 1.5, leaving large *DIST* above a ratio of 1.5.

The first feature defining the appearance of camps at the block level is the *shelter density (DENS)*. It describes the ratio of each block covered by buildings or tents. In light of built-up densities recommended by Sphere, the cut-off points between the low-medium and medium-high thresholds are set to 10 % and 20 % built-up density, respectively. Second, the shelter orientation (*ORI*) indicates how the buildings are oriented towards others in their direct neighbourhood. In the case of planned structures we expect an arrangement of buildings with high geometric alignment, i.e. this parameter indirectly establishes a reference to the formality or informality of an area. A low degree of orientation is present when shelters are not aligned in regular patterns but rather show chaotic structures, meaning that the main axis of each building is neither perpendicular nor parallel to the ones of neighbouring buildings. A high degree of orientation is given when all buildings are aligned perfectly orthogonal or parallel. Medium orientation defines the in-between state. In case shelters feature circular shapes, orientation was determined as the alignment of shelters along straight lines.

At the camp level, the parameter *density homogeneity (HOM)* describes whether the building density varies throughout the camp. It is thus a parameter for the overall visual consistency of the structure in camps. Whenever there is no clear pattern towards one degree of building density, low homogeneity is assigned. Vice versa, high homogeneity is achieved, when density is similar throughout the entire camp. Second on camp level, *camp structure (STR)* indicates whether buildings in the camp show an unclear, fundamental or pronounced alignment with an internal structure. The latter, for example, is found when buildings align in parallel to the road network. Lastly, we assess the *path structure (PATH)*. It describes the geometric alignment of the major path network in the camp varying from a perfect orthogonal alignment to a chaotic path system or even no clearly detectable path network at all.

Table 1. Systematic definition of morphological features and their associated values that form the foundation for the Structure Catalogue. (*AREA* = shelter area, *DIST* = shelter distance, *DENS* = shelter density, *ORI* = shelter orientation, *HOM* = density homogeneity, *STR* = camp structure, *PATH* = path structure).

Scope	Feature	Low/Small	Medium	High/large
Build.	*AREA*	AREA $\leq$ 20 m²	AREA $\leq$ 40 m²	AREA $>$ 40 m²
	DIST	DIST $\leq$ 0.5 shelter axis	DIST $\leq$ 1.5 shelter axis	DIST $>$ 1.5 shelter axis
Block	*DENS*	Block area occupied by shelters $\leq$ 10 %	Block area occupied by shelters $\leq$ 20 %	Block area occupied by shelters $>$ 20 %
	ORI	Chaotic orientation of shelter in their neighbourhood	Some alignment of shelter orientation	Perfect orthogonal alignment of shelter
Camp	*HOM*	$\leq$ 66 % of blocks are of same DENS class	$\leq$ 90 % are of same DENS class	$>$ 90 % of blocks are of same DENS class
	STR	No/low alignment of shelters with internal structure of the camp, e.g. the path network	Some shelters align with internal structure	All shelters align with the internal structure
	PATH	No paths detectable, chaotic path system	Semi-orthogonal aligned path network, or parts of the network being chaotic	Perfectly orthogonal path system

Overall, the SC comprises seven structure parameters representing different morphological features. These provide a template for the quick, yet consistent and detailed visual assessment of the refugee or IDP camp structural appearance. It is also intended to include information useful to guide future developments in image classification approaches as it describes the physical structure of the camps. In this study, the SC will be used to categorize the settlement structures of numerous refugee camps all across the globe.

3. Data and Methods

The methodological approach in this study is structured in three parts – *(1)* Visual image interpretation of refugee camp structures from very high resolution (VHR) satellite imagery, *(2)* evaluation of the SC using reference data, *(3)* subsequent analyses for finding common patterns in refugee camp structures across the globe. For parts *(1)* and *(2)*, three types of data were used – *(a)* UNHCR PoC location data as a starting point for our analysis, *(b)* publicly accessible VHR Satellite imagery for visual interpretation of settlement structures, *(c)* OpenStreetMap (OSM) data for evaluating VII results.

3.1. *Visual image interpretation – Filling the Structure Catalogue*

Ideally, the structure catalogue would be filled by metrics derived from HR geodata on building footprints, road networks and other parameters for all refugee and IDP camps worldwide. However, such data do not exist in a comprehensive database or are not publicly accessible in consistent, up-to-date and exhaustive sources. Digitizing buildings in numerous camps is a very time-consuming task and is therefore also not applicable at scale. This is why we used visual image interpretation of freely available VHR remote sensing imagery from Google Earth in this study, to assess the structural parameters as defined in sec. 2.2.

We based our analysis on a spatial database of locations for PoC published by UNHCR (2022) which listed a total of more than 13,000 places around the world as of October 2020. These are classified into several categories, e.g., "Refugee Camp", "IDP settlement", or "Returnee location". From this database all entries of the "camp" categories were evaluated for their inclusion into the SC (N = 1,606). All the following criteria had to apply for inclusion: (*a*) the camp location coordinates were correctly located, i.e., inside or close to a camp-like structure and settlement structures were visible in HR or VHR imagery at least for one observation time in satellite imagery, (*b*) the structures resemble a coherent (temporary) settlement pattern, (*c*) if located close to a city, the camp structures were clearly distinguishable from formal settlement structures, and (*d*) any reference to the camp/settlement in other data, e.g. OpenStreetMap, Google Maps, media or news outlets, or UNHCR documents was found. Overall, 216 refugee camps and 69 IDP camps from the UNHCR PoC locations database were found to be eligible for the structure catalogue based on these criteria. Figure 3 shows the spatial distribution of the camps across the globe and three examples of refugee camps are illustrated.

For each selected PoC location, all available historical and recent VHR image data were inspected in Google Earth. For every available cloud-free image of the camp, morphological features were visually annotated by an expert based on the classification scheme proposed in sec. 2.2. In total, the Structure Catalogue contains 1,053 unique observations (851 for "refugee camps", 202 for the class "IDP camps") attributing seven structural parameters as ordinal variables: low/small, medium, high/large.

3.2. *Evaluation of refugee camp structures*

In order to validate the VII results, a subset of camps was evaluated using high resolution (HR) reference data. Specifically, these were camps for which HR building footprint data were available from the OpenStreetMap (OSM) Project[3,4]. The evaluation compared visually interpreted results from the SC with quantitative measurements derived from OSM data. Therefore, building footprints, path/road networks and camp outlines were compiled. High resolution reference data were available for 35 camps. The following geographic metrics corresponding to the morphological features in the SC were derived, allowing to test for accuracy and stability of the visual interpretation process.

3.2.1. Measuring morphological features

At the **building level**, we evaluated the validity of the shelter area (*AREA*) derived from VII. The three classes – low, medium, high – are compared to the median shelter area

[3] https://openstreetmap.org

[4] https://wiki.openstreetmap.org/wiki/Refugee/Displaced_Site_Mapping

Figure 3. A selection of different refugee camps (top) and their corresponding appearance in high resolution satellite images (middle). The map overview (bottom) shows all UNHCR PoC locations selected for this study. Satellite data: © Google Earth, Maxar Technologies 2021 & CNES Airbus 2021. Image sources: top left: Image by user Wikipedia User Arre, CC-BY-SA 3.0; top mid: Mark Knobil, CC-BY 2.0; top right: public domain Maaz Hussain (VOA).

($AREA'$) of OSM building footprints in the respective camp. It is defined as

$$AREA' = med\{A_h \mid h = 1, \dots, H\} \tag{1}$$

where A_h is the area of each individual shelter h in square meters and H is the number of all dwellings per camp.

To represent a numeric equivalent for shelter distance (*DIST*) in the SC, we calculate the distance between each building and its closest neighbouring building in relation to the square root of the building's size. The building distance is then averaged per camp as

$$Di_h = \frac{d_h}{\sqrt{A_h}} \tag{2}$$

$$DIST' = \frac{1}{H}\sum_{h=1}^{H} Di_h \tag{3}$$

where A_h is the size of each shelter h and d_h is its distance to the closest neighbouring shelter.

At the **block level**, the visually interpreted shelter density (*DENS*) is compared against the median built-up density of all blocks ($DENS'$). Each block's density is defined as the ratio between the block area and the cumulative area of all buildings in this block:

$$De_b = \frac{1}{A_b} \sum_{h=1}^{H_b} A_h \tag{4}$$

$$DENS' = med\{De_b \mid b = 1, \ldots, B\} \tag{5}$$

where B is the total number of blocks, H_b is the number of dwellings per block, A_h describes the area of each building and A_b is the area of block b.

The building orientation (ORI) describing the alignment of buildings in relation to their neighbourhood is derived from a building's footprint. It is simplified to its minimum area encasing rectangle (Freeman and Shapira, 1975) from which the building's main axis of orientation is derived as ΔX and ΔY. With those, the orientation o can be calculated for each dwelling h and subsequently the orientation difference between each building and its neighbour i can be assessed as $\Delta o_{h,i}$:

$$o = arctan\left(\frac{\Delta Y}{\Delta X}\right) \times \frac{180}{\pi} \tag{6}$$

$$\Delta o_{h,i} = mod(o_h - o_i, 90) \tag{7}$$

The angular difference is then transformed to an orientation index. Its function, $oind(x)$, scales the orientation difference of two objects from orthogonal to chaotic alignment between 0 and 1, cf. Taubenböck *et al.* (2018) eq. 3. A building's orientation is seen in a neighbourhood of the N closest dwellings. Empirically, we found $N = 15$ to be a good trade-off between the stability of the index and computational effort.

$$oind(x) = -|x - 45| \times \frac{1}{45} + 1 \tag{8}$$

$$I_h = \frac{1}{N} \sum_{i=1}^{N} oind\left(\Delta o_{h,i}\right) \tag{9}$$

That is, the building orientation (ORI') of the entire camp can be summarized as

$$ORI' = \frac{1}{H} \sum_{h=1}^{H} I_h. \tag{10}$$

At the **camp level**, the visually derived block homogeneity (*HOM*) is compared against the variance of shelter densities across all blocks as expressed by the standard deviation. Lower variance therefore indicates higher homogeneity. Using the definition of built-up density per block De_b in eq. 4, homogeneity (HOM') is defined as

$$\overline{De} = \frac{1}{B}\sum_{b=1}^{B} De_b \tag{11}$$

$$HOM' = \sqrt{\frac{1}{B}\sum_{b=1}^{B}(De_b - \overline{De})^2} \tag{12}$$

and B is the number of blocks per camp.

The building structure (*STR*), a means of describing the overall structural cohesion of a camp, is evaluated against the standard deviation of all shelter distances Di (see eq. 2) in a camp as STR'.

$$\overline{Di} = \frac{1}{H}\sum_{h=1}^{H} Di_h \tag{13}$$

$$STR' = \sqrt{\frac{1}{H}\sum_{h=1}^{H}\left(Di_h - \overline{Di}\right)^2} \tag{14}$$

The path structure (*PATH*) is measuring how well paths in the camp are aligned to an orthogonal pattern. First, the angle of orientation $o_{i,x}$ is calculated for all line segments at each intersection i using eq. 6. Then, all the segments at each intersection are compared to all adjacent paths k deriving the angular difference by means of eq. 8 and averaged per intersection. Eventually, the road structure ($PATH'$) is aggregated per camp as the median of all path orientation indexes.

$$P_i = \frac{1}{J_i K_i}\sum_{j=1}^{J_i}\sum_{k=1}^{K_i} oind(o_{i,j} - o_{i,k}) \tag{15}$$

$$PATH' = med\{P_i \mid i = 1, \ldots, I\} \tag{16}$$

where I is the total number of intersections per camp, J_i and K_i are the number paths at each intersection i.

These metrics provide a set of quantitative measures to evaluate the validity of the VII approach. This allows for an objective validation of the chosen method of VII in places where highly detailed reference data was available.

3.2.2. Comparing measured morphology to visual interpretation

For the 35 selected camps with all geographic metrics derived from HR geodata, a comparison with the visually obtained parameters of the SC their three-step ordinal scale – low, medium, high – is possible. By contrast, the metric counterparts derived in sec. 3.2.1 feature continuous scales. The goal is to analyse the relationship between these two scales per morphological feature. Although it might be tempting to assume a linear relationship between the three ordinal values in the SC, this would not suit the complex relationship, rendering linear regression unusable for comparison.

Rather, we used ordered logit models, also known as proportional odds logistic regression models, to analyse the relationship between visually interpreted structures and derived metrics (Brant, 1990; Grilli and Rampichini, 2021). Ordered logit models allow assessing the odds, an ordinal target is described by a defined value range of continuous descriptive variables. In particular, they describe the probability P of the outcome Y being less than or equal to a category $j = 1, \dots, J-1$ of J total categories with $P(Y > J) = 0$ as

$$\frac{P(Y \leq j)}{P(Y > j)} \tag{17}$$

with which the log odds (logit) are defined as

$$log\frac{P(Y \leq j)}{P(Y > j)} = logit(P(Y \leq j)). \tag{18}$$

The chosen implementation in R's MASS package (Venables and Ripley, 2002, version 7.3.55) parametrizes the model as

$$logit(P(Y \leq j)) = \beta_{j0} - \eta_1 x_1 - \dots - \eta_p x_p. \tag{19}$$

The resulting proportional odds models fit coefficients that allow for interpreting the relationship between visually interpreted structure parameters in ordinal scale and their measured continuous evaluation metrics. This is done by means of odds ratios as well as p-values and an associated significance estimation for each class transition in the ordinal target.

3.3. *Camp compactness and geometric arrangement*

Observations in the SC aim at providing a multifaceted description of the prevalent structure in refugee camps. Comparing these highly dimensional visually derived parameters on a global scale is challenging. To identify overarching patterns, we reduce the dimensionality and aggregate the seven structure parameters from the SC to describe each settlement's complexity along two major categories: *compactness* and *geometric arrangement*. We combine the following parameters into the aggregate *compactness*: shelter area (*AREA*) as one large building is more compact than multiple buildings of the same cumulative size, the inverse building distance (*DIST*) as a distance-based compactness metric of free spaces, and shelter density (*DENS*) as an areal metric, and homogeneity (*HOM*) of densities in the blocks as a measure of consistency. We define *compactness* as

$$Comp. = \frac{\frac{1}{3}(AREA + (\mid DIST - 4 \mid) + DENS + HOM)}{4}. \tag{20}$$

Similarly, we aggregate *geometric arrangement* from the SC metrics relating to geometric alignment along certain features: building orientation (*ORI*), camp structure (*STR*) and path structure (*PATH*). It is defined as

$$Arr. = \frac{\frac{1}{3}(ORI + STR + PATH)}{3}. \tag{21}$$

In both aggregates, the ordinal values low, medium, and high are equated to numeric values 1, 2, and 3, respectively. Therein, the values are mapped in equal intervals to an ordinal scale low, medium, high. This allows to differentiate between different types of structures and identify patterns by reducing the dimensionality to 2 axes: low, medium and high compactness and geometric arrangement, respectively.

4. Results

The four key results in this study are: *(1)* the Structure Catalogue of refugee and IDP camps filled with the structural features found across the globe, *(2)* a validation of the visually assessed morphological features in the SC using high resolution geodata, *(3)* a description of patterns and variabilities of camp structures across the globe, and *(4)* an assessment of temporal camp dynamics. These results are presented consecutively in the following sections. The SC is made available as part of the supplemental materials of this study.

4.1. *The Structure Catalogue*

In total, the SC contains 1,053 observations from 285 camps, i.e. on average 3.7 observations per camp and 2.45 years apart. For each observation, seven morphological settlement characteristics were assessed through VII of very high resolution satellite imagery. Across the included camps, we found all possible values – low, medium and high – of each morphological feature in the SC (fig. 4), yet there are significant differences in their frequencies, making clear that refugee and IDP camps have more and less characteristic features.

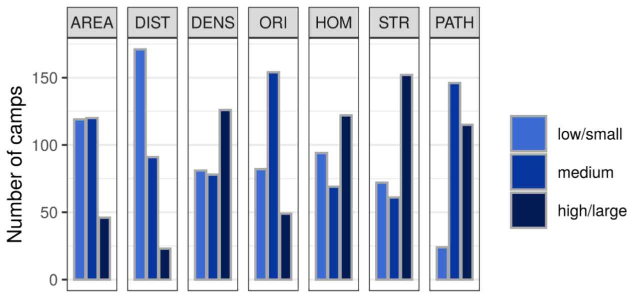

Figure 4. A histogram of the Structure Catalogue by morphological feature. For each camp the most recent observation is used for this histogram. Definitions of low, medium, and high values per feature are detailed in table 1.

Overall, we found that the average building size (*AREA*) tended to be small to medium. Less than one fifth of camps were registered with a large shelter area. Similarly, distances between buildings (*DIST*) were low to medium in most camps. Small building sizes and small distances reflect the dominant shelter types, i.e., small tents, huts or containers that make up the bulk of the residential shelters in refugee camps. Nevertheless, there are exceptions to this trend. Larger buildings are defining the structure in cases where efforts are made to build large facilities. These feature higher building qualities, better materials and larger buildings.

At the block level, camps tend to show high built-up densities (*DENS*). However, this trend is less pronounced than with *DIST*, e.g, as a result of organic low-density sprawl at the fringe of camps. Building orientation (*ORI*) had medium values for more than half of the settlements. Camp homogeneity (*HOM*) was evaluated rather bipolar as low or high values were found more frequently than medium. Planned, structured settlement pattern dominate our sample of camps; however, about one-third of all camps are measured with a complex, less homogeneous pattern. Building alignment alongside structural elements like roads (*STR*) was high in more than half of the camps. Less than 10 percent of camps did not show a clear path structure (*PATH*); consequently, in most cases *PATH* was evaluated to medium or high values, meaning semi-orthogonal and orthogonal layouts were dominant.

For example, the camps in figure 3 had the following morphology: Awserd, Algeria (in October 2018) featured medium *AREA*, medium *DIST*, medium *DENS*, medium *ORI*, low *HOM*, medium *STR*, medium *PATH*. Touloum, Chad (in December 2018) had small *AREA*, high *DIST*, low *DENS*, medium *ORI*, high *HOM*, medium *STR*, low *PATH*. Nayapara, Bangladesh (in January 2020) featured large *AREA*, low *DIST*, high *DENS*, high *ORI*, high *HOM*, high *STR*, medium *PATH*.

4.2. *Evaluation*

The visual assessment of the settlement structures in camps corresponds to the measured numeric variables in the geodata. The evaluation of the VII results reveals that the structure parameters follow expected trends (fig. 5). Distinct linear or exponential relationships are evident for all features but *STR*. Variances were generally low except in cases with low numbers of observations, e.g. large shelter area (*AREA*).

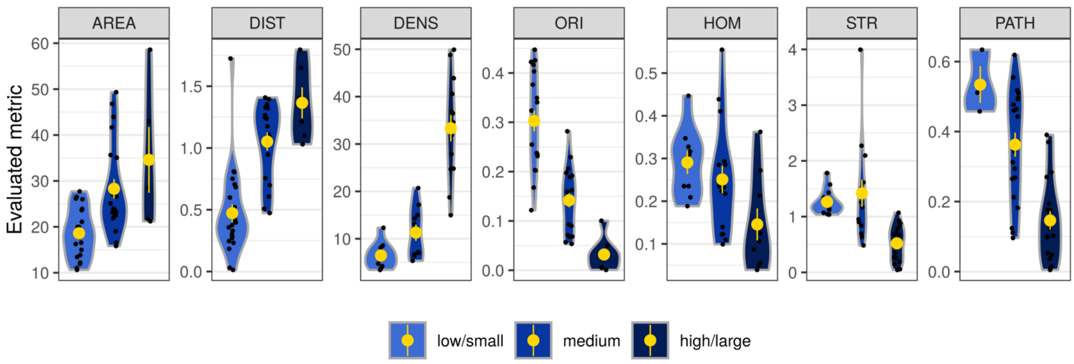

Figure 5. Comparison of visually assessed ordinally scaled morphological parameters in the SC and the measured evaluation metrics derived from geodata. Violin plots visualize the distribution of values across the evaluated metrics defined in sec. 3.2: shelter size *AREA*, shelter distance *DIST*, shelter density *DENS*, shelter orientation *ORI*, density homogeneity *HOM*, camp structure *STR*, path structure *PATH*. Yellow dots with antennas indicate the per-group mean and variance, respectively.

The proportional odds logistic regression (fig. 6) shows that most features have distinct per-class odds for the low, medium and high classes. Each class clearly populates a dedicated interval along the measured validation metric. The only exception to this is medium *STR* which does not clearly protrude by its proportional odds. The arrangement of the proportional odds curves from low to high varied across the morphological features consistently with the definitions of the visually derived and the measured features. For example, the odds of a camp being considered having low, medium and high *DIST* was highest in camps with measured average normalized building distances (cf. eq. 3) between 0 and 0.5, 0.5 and 1.45, and above 1.45, respectively. Thus, it was mostly matching the intended definition in table 1. Similarly, a camp was considered having small, medium and large sized buildings when average building sizes were measured to be around ≤ 25 m², ≤ 40 m², and

> 40 m², respectively.

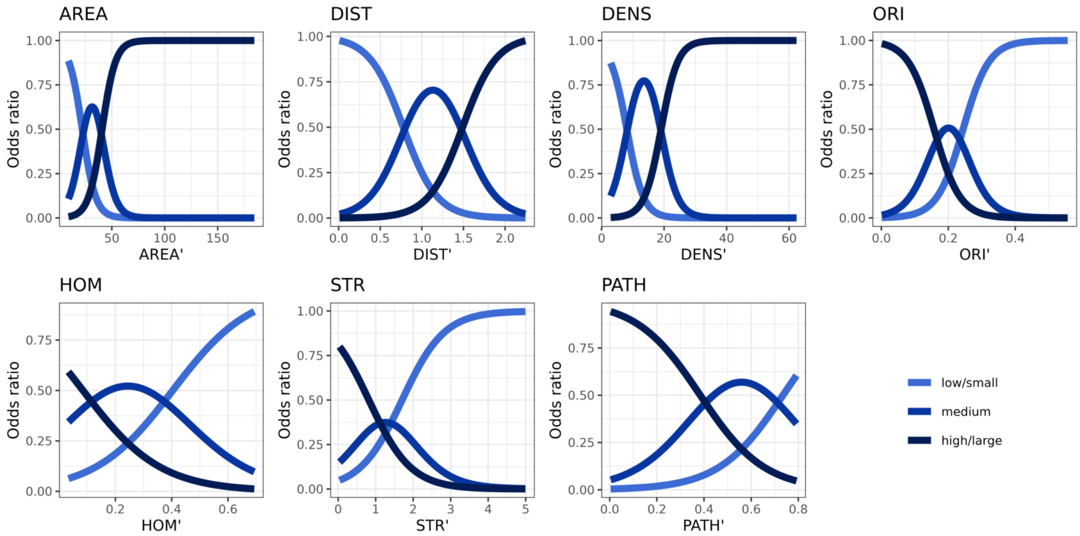

Figure 6. Results of the proportional odds logistic regression. The plots show the odds ratios (y-axis) of each evaluated metric derived from OSM data (x-axis, see sec. 3.2) describing the discrete value of SC features derived from VII (colours, see sec. 2.2): shelter size *AREA*, shelter distance *DIST*, shelter density *DENS*, shelter orientation *ORI*, density homogeneity *HOM*, camp structure *STR*, path structure *PATH*.

The varying magnitude of the odds ratios (cf. table 2) was caused by the differences in definition and especially the scale of units between the visually derived and the measured features. For example, with an increase in average shelter size of 1 m², the odds of a camp being evaluated with a higher value in the VII increased by 17 %. Similarly, the odds of a camp being evaluated with a higher density were 1.45 times higher for every percent increase in median building density in the camp. Most p-Values indicated highly significant results for the low/medium and medium/high class thresholds except for the *HOM* medium/high threshold, further highlighting the conceptual complexity of the parameter and relation to the evaluated metric.

Table 2. Results of the proportional odds logistic regression analysis. Odds ratio, Confidence intervals (CI) and p-Values for the class thresholds between low & medium and medium & high transitions are provided alongside significance levels (*** $p < 0.001$, ** $p < 0.01$, * < 0.05).

Metric	Odds Ratio	CI 2.5 %	CI 97.5 %	p-Value low | medium	p-Value medium | high
AREA	1.1702	1.0905	1.2759	0.00028 ***	0.00000 ***
DIST	135.75	20	1640.23	0.00004 ***	0.00000 ***
DENS	1.4543	1.2200	1.9503	0.00368 **	0.00071 ***
ORI	6.6×10^{-12}	2.2×10^{-17}	8.5×10^{-8}	0.00000 ***	0.00013 ***
HOM	7.0×10^{-4}	1.2×10^{-6}	1.7×10^{-1}	0.00089 ***	0.38330
STR	0.170	0.0470	0.4816	0.00005 ***	0.01776 *
PATH	6.3×10^{-4}	5.1×10^{-6}	0.0350	0.00000 ***	0.00069 ***

4.3. *Global patterns in structural morphology*

Aggregated patterns of the overall morphological structure were attained by combining the morphological features into compactness and geometric arrangement (see fig. 7). The distribution of IDP and refugee camps across these two parameters highlighted that all possible combinations of compactness and arrangement are well represented. The building footprint plans in 7 a) exemplify the differences in settlement morphology. Interestingly, the combinations 'high arrangement–low compactness' and 'low arrangement–high compactness' were found less frequently across the observed camps in the SC (see fig. 7 b)). Also, no notable differences between refugee and IDP camps could be identified.

Once mapped (see fig. 7 c)), the different structural groups, as defined along the two-dimensional space of compactness and geometric arrangement, become apparent in their spatial patterns across the globe. For example, along Turkey's southern border we mostly found highly compact and highly arranged camps. In fact, being built by the Turkish government (Yavcan, 2016), most resemble a planned and built-from-scratch layout that features high density and strict alignment of buildings along the checker board-like road network similar to the Cevdetiye Camp (see fig. 1). Similarly, along the western border of Thailand as well as in southern Bangladesh, we saw a spatial cluster of camps with high compactness and medium arrangement.

Camps with lower levels of arrangement and lower compactness were found predominantly in Central Africa and the Sahel region. The varying degrees of alignment could also be indicative of the different evolution of these settlements, some of them existing for decades. In western Africa, again, we found a spatial cluster of camps featuring high arrangement and high compactness. Importantly, however, we found none of these regional clusters are exclusive. Rather, in every region we found camps diverging from the majority of structures in that region.

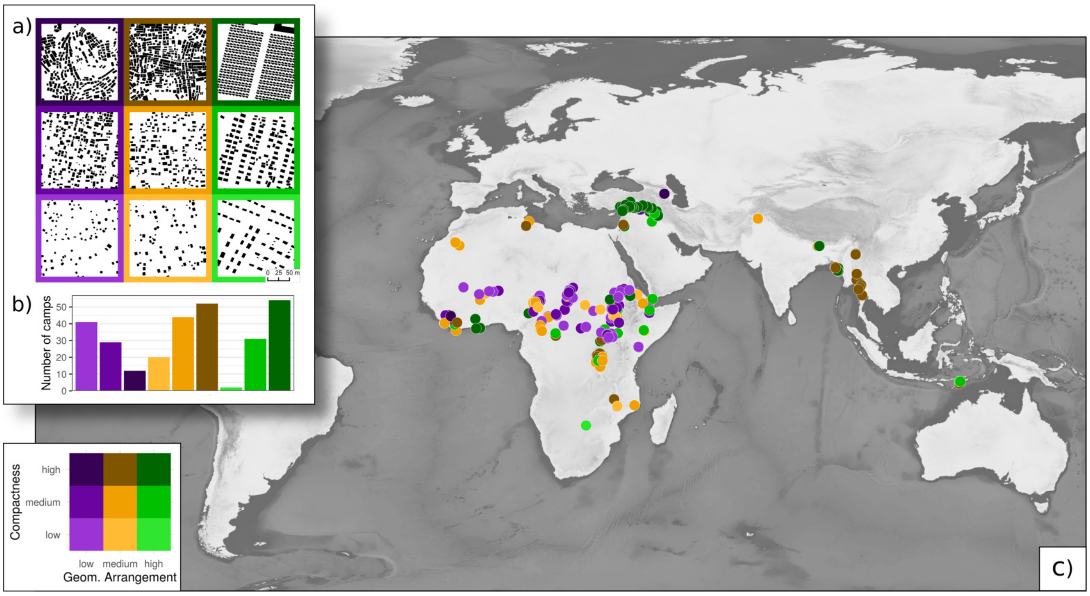

Figure 7. Overview of the structure catalogue. a) Examples of building footprints of camps along the two-dimensional compactness and geometric arrangement scale. b) Frequency of camps in each compactness-arrangement class. c) World map with IDP and Refugee camps in different locations with compactness and geometric arrangement classification.

4.4. *Temporal dynamics of camp structures*

45 of the 285 camps in our study have been recorded only once. 240 camps were observed multiple times. Across camps with multiple observations, 60 % of camps ($N = 144$) experienced at least slight changes in one or more of the seven morphological features covered by

the SC between observations. For readability, table 3 summarizes frequencies of all changes in camp structure by means of the aggregates compactness and geometric arrangement. These showed that, overall, arrangement decreases more often than it increases (see Σ_{arr}) over time. An inverse trend was found for the compactness of the camps, which tended to increase (see Σ_{com}). Overall, arrangement was found to be more stable compared to compactness. 157 camps did not change arrangement noticeably as opposed to 110 which featured stable compactness.

Table 3. Cross tabulation of changes in structure by geometric arrangement (Arr.) and compactness (Com.) in all 240 camps that were observed multiple times. 96 camps did not show any change. Changes are summarized as decrease (decr.), no change (no chg.) or increase (incr.).

Arr. \ Com.	**decr.**	**no chg.**	**incr.**	Σ_{arr}
decr.	23	8	21	*52*
no chg.	28	96	33	*157*
incr.	7	6	18	*31*
Σ_{com}	*58*	*110*	*72*	**240**

Yet, these changes were often minor and only were reflected by the slight change of one morphological structure parameter in the SC. In fact, only 34 (ca. 15 %) of the camps changed so significantly to be registered in a different class within the compactness-arrangement scale (see fig. 8). Thus, most camps revealed a stable settlement pattern in their compactness-arrangement class over time. Interestingly, camps with low arrangement (purple colours) were adapted to a more geometric and arranged patterns in only very few cases. In turn, medium and highly arranged camps (yellow and green arrows, respectively) show higher dynamics. This is likely caused by sprawl or densification processes in these camps. For example, 6 camps that were first observed with medium compactness and medium arrangement (medium yellow, 6-8 o'clock positions) increased their compactness over time, landing in the dark yellow target area (4-6 o'clock positions).

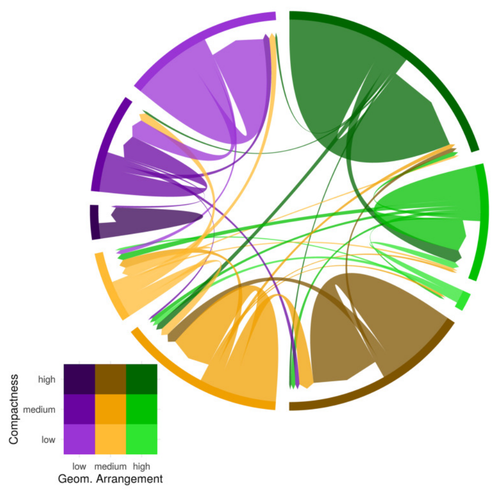

Figure 8. Changes in the structure of refugee and IDP camps by means of compactness and arrangement from the first to the last observation (N = 240). Colours are chosen as in fig. 7: brighter to darker colours (low to high compactness), purple (low geometric arrangement), yellow (medium geometric arrangement), green (high geometric arrangement). Each arrow describes the transition from one compactness-arrangement class to another. Quantities are represented by thickness. Most camps do not change their class, indicated by the thick arrows in each class pointing to itself.

5. Discussion

5.1. *The Structure Catalogue*

We compiled the SC as an extensive database for camp morphologies in refugee settlements around the world. The SC systemizes structural types in a spatial-quantitative manner. The measured high diversity of the structures across all camps is intended to add to the literature in two ways: On the one hand, the SC allows documenting the variability of settlement patterns across space and the dynamics camp structures over time using a spatial-quantitative method. Furthermore, it allows capturing the spatial distribution of camp structures across the globe. On the other hand, it can serve as a reference database to train supervised image analysis methods in the field of machine learning specifically on the target objects and to keep an eye on their variability.

From a structural point of view, buildings in environments with limited or restricted access to building material are typically constructed of scraps of timber, plywood or plastic sheeting (Inter-Agency Shelter Sector Corrdination Working Group, 2018) explaining small shelter sizes. We found a tendency to high homogeneity, geometric arrangements and geometric path structure across in camps with a planned, organized, and well funded development process. Especially in highly dense settings, buildings were found to be located along paths or roads, towards central squares and the likes with no room to spare. However, there exists no uniformity. Building density and orientation were also found to be influenced by the underlying topography; in this analysis, however, these effects were not taken into account.

Despite the recent advances in technologies, satellite imagery is not able to capture certain parts of settlement structures, such as the availability of certain amenities like electricity, fresh water and sewage. This study is therefore limited by design to the aspects visible in very high resolution imagery i.e. the building structures and the path patterns. Furthermore, the description is solely based on visual appearance and does not intend to elaborate on political, legal or ethical issues with the camps.

The selection of the camps was conducted using criteria described in sec. 3.1. Even though we sought to find an objective set of rules determining which camps to include from the UNHCR PoC locations data, we acknowledge that these rules may be subject to selection bias. The following aspects influenced our selection: the camp type in the underlying UNHCR PoC locations dataset, VHR image availability at the camp location, spatial inaccuracy of the original UNHCR PoC locations data, and whether camps could be delineated from adjacent formal settlement structures. What's more, VHR image availability further limits the analysis to the period of roughly two decades as VHR imagery was not available prior to the early 2000s. The SC aims to provide an evaluation of the status quo of settlement patterns as seen from VHR satellite imagery. It will be interesting to see in future studies, whether these patterns match or deviate from the existing standards like in the Sphere guidelines. Recent advances like with UAV imagery even allow increasing the spatial resolution for such analyses (e.g. Chan *et al.*, 2022). Beyond that, we suggest additional research to analyse settlement patterns in relation to context and geographical setting, e.g. planning guidelines, proximity to urban centres among many more.

In this study only dedicated refugee and IDP camps were analysed. However, as most refugees and IDPs live in urban settings, we acknowledge that this only captures the living environment of a small part of the refugees and IDPs worldwide (Inter-Agency Shelter Sector Corrdination Working Group, 2018; UNHCR, 2021a). Furthermore, we did not include information about the building materials used for shelters in the camps. Across the camps we found a wide variety of materials, but as it was difficult to find reliable information for their evaluation, they were not included in the SC.

5.2. *Evaluation*

In this study, we described settlement structure in camps in two ways: VII and geographic metrics derived from vector geodata. While the latter yields very high metric accuracy and allows for describing morphological features along continuous axes, it requires high-quality, up-to-date geographic vector data. These are, however, often not freely available and sometimes even inexistent. We found refugee camps often not included in openly available datasets like OpenStreetMap, despite dedicated efforts by the Missing Maps initiative or work by the Humanitarian OpenStreetMap Team[5]. Even with recent advances in large-scale building stock data on continental scales (e.g. Sirko *et al.*, 2021; Zhu *et al.*, 2022), such data are still not able to capture the fine details of the highly complex settlements found in refugee camps around the globe. Beyond this, it has been reported that refugee camps are typically misrepresented in large scale settlement data products (Van Den Hoek and Friedrich, 2021). Hence, VII offers a way of quickly assessing settlement structure in areas where high quality vector data is missing.

We want to acknowledge that previous studies, e.g., by Kraff *et al.* (2020b) have highlighted the uncertainty of manual VII as a means of data collection. We therefore carefully systemized the morphological structural features into a framework of ordinal scales suitable for visual image interpretation and ensured its stability by evaluating it using high-resolution geographic data. Our comparison of manual classification and quantitative analysis based on high-resolution geospatial data showed that at this level of analysis, manual interpretation yielded reliable results. The probabilistic ordinal logistic regression is able to attribute the ordinal relationship of the visually derived classes *low/small*, *medium* and *high/large* along the continuous scales of the derived metrics. Only the values of homogeneity (*HOM*) and settlement structure (*STR*) showed some levels of reduced reliability when compared to measured values. This can be attributed to the conceptual complexity in the definition of the respective morphological features. Further, the statistical stability of the results could be increased by adding more camps to the evaluation.

Overall, bridging the gaps in existing geographic data, we deem VII a reliable tool to provide useful information for many camps worldwide. Selecting 285 camps from 1,606 candidates as well as their structural evaluation is estimated to take about 25 working days for a trained expert. While this is still a lot of work, it is significantly faster compared to manually digitizing building footprints for each of the camps, let alone multiple temporal observations. We conclude that the resulting SC is providing an empirically proven, reliable description of measurable settlement structure patterns, albeit along an ordinal scale.

5.3. *Global patterns in structural morphology*

To our knowledge, the SC is the first global database of settlement structures in refugee and IDP camps. As such it allows for better understanding of overarching patterns across the globe. The seven morphological parameters captured by the SC, describe different aspects of the structural layout in the camps in great detail. When seeking to identify global patterns in refugee camp structure, however, this high dimensionality makes the analysis complex. By summarizing the seven morphological features into a two-dimensional descriptor of camp compactness and geometric arrangement, the assessment of settlement structure was made accessible.

Before we used the two-dimensional approach to aggregate the results by arrangement and compactness, we experimented with clustering techniques for dimensionality reduction.

[5] https://www.hotosm.org

Specifically, we tried to apply agglomerative hierarchical clustering. The rationale behind this approach was to identify clusters of camps with similar structural parameters. However, the results did not show coherent groups of camps, as the mathematical nature of clustering did not capture the conceptual and structural relationship between the individual morphological features. Further, standardized methods for finding the optimal number of clusters showed high variations ranging between two and more than a dozen clusters. Upon visual inspection of different clustering results, i.e. varying number of clusters, we found no meaningful explainable differences between some clusters.

Our results with the aggregated two-dimensional approach of geometric arrangement and compactness show that there is, expectedly, no one-size-fits-all description of the structure in a refugee or IDP camp that applies everywhere. However, using this scale we were indeed able to identify some regional patterns. In general, we found that certain structural compositions are regionally clustered; for example, highly compact and aligned along the Turkish-Syrian border and highly dense along the Thailand-Myanmar border but with less geometric arrangement owing to more rugged terrain; or highly diverse, often less dense and more geometrically chaotic settlement patterns in Subsahara Africa of more informal character that reflect the long and complex history of migration in the region as well as precarious humanitarian funding (e.g. in Uganda, Ahimbisibwe, 2019). However, it needs to be clearly stated that these are only trends and different types of structures are found in all of these regions, too. This shows that one should infer a camp's structure based on the camps close by, as Tobler's first law of geography would suggest. Rather, the structure of each camp needs to be assessed separately.

5.4. *Temporal dynamics of camp structures*

Refugee camps are often built as temporary settlements. As such, they sometimes undergo many stages of construction, changing complexity, density, and even building material, like many poor neighbourhoods around the world (Kraff *et al.*, 2020a). These changes are caused by influx of people and following re-densification, sprawl or (partial) deconstruction of the camp.

The multitemporal nature of the SC allows for tracking these structural changes across multiple observations. Against our expectations, most settlements only show slight changes to the structure. Generally, temporal evolution tends to lead to (but is not limited to) higher compactness and lower arrangement of the settlements. More significant changes, which we saw in our study, were expressed through a change along the two-dimensional ordinal compactness-arrangement scale, yet they are rare.

Overall, the high percentage of camps that show any change during their time of existence is indicative of highly dynamic settlement structures. It is these dynamics that are crucial to include in future datasets when designing automated settlement classifications. Otherwise, the misrepresentation of refugee and IDP settlements described by Van Den Hoek and Friedrich (2021) will remain and eventually lead to biased geographic assessments of dimensions or locations. Only by the integration of this knowledge, future automated mapping techniques employing ML can, as demonstrated by e.g. Quinn *et al.* (2018), account for these temporal changes. Thus, our results can be used to inform the creation of future automated mapping applications in complex settlement structures such as refugee and IDP camps.

6. Conclusion and Outlook

In this study, we developed a framework to reliably assess the settlement morphology in refugee and IDP camps around the globe to create the *Structure Catalogue* (SC). Derived from VII of multitemporal VHR imagery, it contains a collection of seven morphological features for 285 camps across a total of 1,053 observations. These were further aggregated into a compactness vs. geometric arrangement scale to describe the variability of existing patterns in refugee and IDP camp morphology. The SC thus allows for analyses of overarching patterns on a global scale, it provides a conceptual frame and a methodological workflow, and therefore allows closing the previously existing knowledge gaps on existing settlement patterns. Based on a rigorous evaluation of results acquired through visual image interpretation with high resolution vector data, we prove that VII provides stable and reliable means to collect information about settlement structures. Yet, compared to manual digitization efforts the process outlined in this study was significantly less resource intensive and therefore provides a useful tool for creating reference data in an age of rapid growth of ML applications.

The spatial analysis of refugee and IDP camps around the globe showed that they vary drastically in terms of settlement structure. There was no one-size-fits-all description of the complex and diverse morphological parameters. The SC documents spatial patterns in terms of compactness and geometric arrangement of the camps. Overall, structures in these settlements consisting of mostly single-story buildings range from very densely to sparsely built. In most camps shelters are small and built with small distances between each other. Almost half of the camps feature a highly organized path structure. Still, a wide variety of geometric alignments, from complex to highly organized, were present. Several geographic clusters of similar structure arose from the SC, the underlying mechanisms and determinants of which, such as topography, history, funding, socio-economic and political setting will be an interesting extension the SC in future research. The multitemporal nature of the SC allowed for identification of changes in camps structures. We found that about 60 percent of camps showed at least slight changes throughout the observed time frame. Further, about 15 percent of camps showed stronger changes along the compactness-arrangement scale. This means that analyses of refugee and IDP camps must take the different structures and dynamics into account in search of automated mapping techniques, e.g. in remote sensing image classification applications, to ensure high quality and reliability in generated geoinformation products.

The results of VII are always subject to the interpreter's experience and hence might be biased by subjective perception. In this study, VII was conducted by a single interpreter with experience in GIScience. For future studies, we recommend performing a validation for different interpreters. Future work is suggested to focus on further expanding the concept developed in this study to other UNHCR PoC locations and possibly other geographic databases. Besides, the SC is intended to lay ground to large scale GIScience and remote sensing applications by serving as a global reference database and conceptual and methodological framework for analysis and monitoring of camp structures. We aim to foster the development of automated frameworks for differentiation between different kinds of settlement structures using open-access geographic data. This can be used to investigate the gradient of structural dynamics to identify rapid changes in settlement structure, e.g. caused by (natural) disasters, reconstruction or demolition. Thus, the SC can be used as additional information layer that might support decision-making for humanitarian actors, NGOs or governmental institutions to help the most vulnerable populations and those in need fulfilling their human rights obligations.

Acknowledgements

We thank Ricardo Göhler and Ebru Koç for their assistance. We acknowledge the data provided by the OpenStreetMap project and its contributors under the terms of the Open Data Commons Open Database License (ODbL).

Disclousure statement

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript, or the decision to publish the results.

Funding

This study has been conducted as part of the projects MIGRAWARE (Grant No. 01LG2082C), funded by the German Federal Ministry of Education and Research (BMBF) as part of the programme WASCAL WRAP 2.0, and the European Union's Caroline Herschel Framework Partnership Agreement on Copernicus User Uptake under grant agreement No FPA 275/G/GRO/COPE/17/10042, project FPCUP (Framework Partnership Agreement on Copernicus User Uptake), Action 2019-2-11 "Downstream service / application development for monitoring of environmental indicators (Africa)". The study is also part of the Project "Demand-driven data services for humanitarian aid (Data4Human)" at the German Aerospace Center (DLR).

Data and code availability statement

The data and code that support the findings of this study are available for further research at https://doi.org/10.6084/m9.figshare.c.6207238. The collection includes

- the Structure Catalogue featuring the following attributes: an object ID, camp name, date of observation (accurate to months), the collected structure parameters AREA, DIST, DENS, ORI, HOM, STR, and PATH per observation in numeric values 1=low/small, 2=medium, 3=high/large, a rough description of the prevalent (most common) building materials (BUILD_MATERIAL), the aggregated compactness and arrangement measures as well as geographic coordinates (geogr. WGS 84, EPSG 4326),
- R code supporting the methodology of this study,
- supplementary geographic data required for running the code.

Notes on contributors

Matthias Weigand studied Geography (BSc) with a focus on remote sensing at the Julius-Maximilians-Universität Würzburg, Germany (JMU) and Geoinformatics (MSc) at the University of Augsburg, Germany. Currently, he is a research assistant and PhD student at the Earth Observation Center (EOC) of the German Aerospace Center (DLR). His research focuses on combining large scale geographic data, machine learning, and geostatistics for analysing and monitoring the human habitat.

Matthias Weigand developed the methodology of the study, wrote software for the spatial and statistical analyses, drafted and edited the article, contributed graphical designs and acts as corresponding author.

Simon Worbis studied Applied Geodesy and Geoinformatics (BEng) at the Munich University of Applied Sciences where he is currently studying for a master's degree in Geomatics (MEng). His research interests focus on remote sensing, machine learning techniques and geostatistics.
Simon Worbis contributed by collecting the data, developing software for spatial and statistical analyses, and reviewing the manuscript.

Marta Sapena, engineer in Geodesy and Cartography completed her Ph.D. in Geomatics Engineering at the Polytechnic University of Valencia, Spain. Currently, she is a postdoctoral researcher at the Earth Observation Center (EOC) of the German Aerospace Center (DLR). Her research interests include the development of methodologies that allow relating the spatial structure of urban areas and their evolution to geographic, demographic, and socioeconomic variables, assessing exposure and vulnerability to natural hazards, and mapping and monitoring urbanisation through remote sensing.
Marta Sapena contributed to the study through consulting formal analyses and critical review of the manuscript.

Hannes Taubenböck is affiliated with the German Aerospace Center (DLR) and the Julius-Maximilians-Universität Würzburg (JMU). At DLR he is heading the department "Georisks and Civil Security" within the German Remote Sensing Data Center (DFD) and at JMU he is professor holding the chair "Global Urbanization and Remote Sensing".
Hannes Taubenböck contributed the research idea, the conceptual approach, the acquisition of funding, the supervision of the formal analysis, and reviewing of the manuscript.

References

Ahimbisibwe, F., 2019. Uganda and the refugee problem: challenges and opportunities. *African Journal of Political Science and International Relations*, 13 (5), 62–72.

Aravena Pelizari, P., *et al.*, 2018. Multi-sensor feature fusion for very high spatial resolution built-up area extraction in temporary settlements. *Remote Sensing of Environment*, 209, 793–807.

Aylett-Bullock, J., *et al.*, 2021. Operational response simulation tool for epidemics within refugee and IDP settlements: A scenario-based case study of the cox's bazar settlement. *PLOS Computational Biology*, 17 (10), e1009360.

Brant, R., 1990. Assessing proportionality in the proportional odds model for ordinal logistic regression. *Biometrics*, 46 (4), 1171.

Braun, A., Fakhri, F., and Hochschild, V., 2019. Refugee camp monitoring and environmental change assessment of kutupalong, bangladesh, based on radar imagery of sentinel-1 and ALOS-2. *Remote Sensing*, 11 (17), 2047.

Chan, C.Y.C., *et al.*, 2022. Investigating the capability of uav imagery for ai-assisted mapping of refugee camps in east africa. *In*: M. Minghini, P. Liu, H. Li, A.Y. Grindberger and L. Juhász, eds. *Proceedings of the Academic Track at State of the Map 2022*, August, Florence, Italy. Zenodo, 45 – 48.

Cornebise, J., Oršolić, I., and Kalaitzis, F., 2022. Open high-resolution satellite imagery: The worldstrat dataset – with application to super-resolution.

Freeman, H. and Shapira, R., 1975. Determining the minimum-area encasing rectangle for an arbitrary closed curve. *Communications of the ACM*, 18 (7), 409–413.

Georganos, S., *et al.*, 2021. Is it all the same? mapping and characterizing deprived urban areas using WorldView-3 superspectral imagery. a case study in Nairobi, Kenya. *Remote Sensing*, 13 (24), 4986.

Grilli, L. and Rampichini, C., 2021. Ordered logit model. *In*: *Encyclopedia of quality of life and well-being research*. Springer International Publishing, 1–4.

Inter-Agency Shelter Sector Corrdination Working Group, 2018. *Guidelines for the fire prevention, preparedness, and response (fppr)*. Temporary Technical Committee Led & Developed by Save the Children International (SCI). Available from: https://data2.unhcr.org/en/documents/download/62513.

International Organization for Migration, 2021. *Environmental migration disaster displacement and planned relocation in west aftrica* [IOM – International Organization for Migration, Geneva, Switzerland]. Geneva, Switzerland: International Organization for Migration (IOM). Available from: https://publications.iom.int/system/files/pdf/Environmental-Migration-Disaster-Displacement-in-West-Africa.pdf.

Jochem, W.C., *et al.*, 2021. Classifying settlement types from multi-scale spatial patterns of building footprints. *Environment and Planning B: Urban Analytics and City Science*, 48 (5), 1161–1179.

Jochem, W.C. and Tatem, A.J., 2021. Tools for mapping multi-scale settlement patterns of building footprints: An introduction to the r package foot. *PLOS ONE*, 16 (2), e0247535.

Kraff, N.J., Wurm, M., and Taubenböck, H., 2020a. The dynamics of poor urban areas - analyzing morphologic transformations across the globe using earth observation data. *Cities*, 107, 102905.

Kraff, N.J., Wurm, M., and Taubenböck, H., 2022. Housing forms of poverty in europe - a categorization based on literature research and satellite imagery. *Applied Geography*, 149, 102820.

Kraff, N.J., Wurm, M., and Taubenbock, H., 2020b. Uncertainties of human perception in visual image interpretation in complex urban environments. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 13, 4229–4241.

Kuffer, M., Barros, J., and Sliuzas, R.V., 2014. The development of a morphological unplanned settlement index using very-high-resolution (VHR) imagery. *Computers, Environment and Urban Systems*, 48, 138–152.

Lang, S., *et al.*, 2019. Earth observation tools and services to increase the effectiveness of humanitarian assistance. *European Journal of Remote Sensing*, 53 (sup2), 67–85.

Lang, S., *et al.*, 2010. Earth observation (EO)-based ex post assessment of internally displaced person (IDP) camp evolution and population dynamics in zam zam, darfur. *International Journal of Remote Sensing*, 31 (21), 5709–5731.

McAuliffe, M., Lee, T., and Abel, G., 2021. Migration and migrants: A global overview. *In*: M. McAuliffe and A. Triandafyllidou, eds. *World migration report 2022*. Geneva: International Organization for Migration (IOM), Ch. 2, 21–57.

McAuliffe, M. and Triandafyllidou, A., 2021. Report overview: Technological, geopolitical and environmental transformations shaping our migration andmobility futures. *In*: M. McAuliffe and A. Triandafyllidou, eds. *World migration report 2022*. Geneva: International Organization for Migration (IOM), Ch. 1, 1–17.

Nasir, M., *et al.*, 2022. Dwelling type classification for disaster risk assessment using satellite imagery.

Quinn, J.A., *et al.*, 2018. Humanitarian applications of machine learning with remote-sensing data: review and case study in refugee settlement mapping. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376 (2128), 20170363.

Ramadan, A., 2012. Spatialising the refugee camp. *Transactions of the Institute of British Geographers*, 38 (1), 65–77.

Sirko, W., *et al.*, 2021. Continental-scale building detection from high resolution satellite imagery. online, https://arxiv.org/pdf/2107.12283v2.pdf, July. Available from: https://arxiv.org/pdf/2107.12283v2.pdf.

Sphere Assotication, ed., 2018. *The sphere handbook: Humanitarian charter and minimum standards in humanitarian response*. 4th ed. Geneva, Switzerland.

Stark, T., *et al.*, 2020. Satellite-based mapping of urban poverty with transfer-learned slum morphologies. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 13, 5251–5263.

Taubenböck, H. and Kraff, N.J., 2014. The physical face of slums: a structural comparison of slums in mumbai, india, based on remotely sensed data. *Journal of Housing and the Built Environment*, 29 (1), 15–38.

Taubenböck, H., Kraff, N., and Wurm, M., 2018. The morphology of the arrival city - a global categorization based on literature surveys and remotely sensed data. *Applied Geography*, 92, 150–167.

Taubenböck, H., *et al.*, 2019. A new ranking of the world's largest cities—do administrative units obscure morphological realities? *Remote Sensing of Environment*, 232, 111353.

Tomaszewski, B., *et al.*, 2016. Infrastructure evolution analysis via remote sensing in an urban refugee camp – evidence from za'atari. *Procedia Engineering*, 159, 118–123.

UNHCR, 2021a. Global report 2020. online, https://reporting.unhcr.org/sites/default/files/gr2020/pdf/GR2020_English_Full_lowres.pdf. Available from: https://reporting.unhcr.org/sites/default/files/gr2020/pdf/GR2020_English_Full_lowres.pdf.

UNHCR, 2021b. Global trends – forced displacement report in 2020. online, https://www.unhcr.org/60b638e37/unhcr-global-trends-2020. Available from: https://www.unhcr.org/60b638e37/unhcr-global-trends-2020.

UNHCR, 2022. UNHCR GIS DATA: Refugee camps and other people of concern's locations. online, https://www.arcgis.com/home/webmap/viewer.html?webmap=24cad2271eaf4219832bf82da5803193, accessed 2022-02-16. Available from: https://www.arcgis.com/home/webmap/viewer.html?webmap=24cad2271eaf4219832bf82da5803193.

Unite Nations Department of Economic and Social Affairs (UN DESA), 2020. International migration stock. online, https://www.un.org/development/desa/pd/content/international-migrant-stock, accessed 2022-02-08. Available from: https://www.un.org/development/desa/pd/content/international-migrant-stock.

Van Den Hoek, J. and Friedrich, H.K., 2021. Satellite-based human settlement datasets inadequately detect refugee settlements: A critical assessment at thirty refugee settlements in uganda. *Remote Sensing*, 13 (18), 3574.

Venables, W.N. and Ripley, B.D., 2002. *Modern applied statistics with s*. 4th ed. New York: Springer. ISBN 0-387-95457-0, Available from: https://www.stats.ox.ac.uk/pub/MASS4/.

Wang, J., *et al.*, 2022. On the knowledge gain of urban morphology from space. *Computers, Environment and Urban Systems*, 95, 101831.

Weigand, M., *et al.*, 2020. Spatial and semantic effects of LUCAS samples on fully automated land use/land cover classification in high-resolution Sentinel-2 data. *International Journal of Applied Earth Observation and Geoinformation*, 88, 102065.

Witmer, F.D.W., 2015. Remote sensing of violent conflict: eyes from above. *International Journal of Remote Sensing*, 36 (9), 2326–2352.

Wurm, M., *et al.*, 2019. Semantic segmentation of slums in satellite images using transfer learning on fully convolutional neural networks. *ISPRS Journal of Photogrammetry and Remote Sensing*, 150, 59–69.

Wurm, M., *et al.*, 2017. Slum mapping in polarimetric SAR data using spatial features. *Remote Sensing of Environment*, 194, 190–204.

Yavcan, B., 2016. On governing the syrian refugee crisis collectively: The view from turkey. online, http://nearfuturesonline.org/wp-content/uploads/2016/01/Yavcan_04.pdf, accessed 2022-02-10.

Zhu, X.X., *et al.*, 2022. The urban morphology on our planet – Global perspectives from space. *Remote Sensing of Environment*, 269, 112794. Available from: https://www.sciencedirect.com/science/article/pii/S0034425721005149.