

Configurational Morphogenesis under Rapid Expansion: Access Network Adaptations in Kutupalong Refugee Camp, Bangladesh

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Abstract

This paper presents a multi-temporal, multi-layered analysis of the configurational morphogenesis of Kutupalong refugee camp in Bangladesh as a critical case study. In particular, it investigates the configurational adaptations of the access network from incremental growth to rapid expansion, and the extent to which topography has enabled or constrained the network's spatial transformations over time. The study adopts an exploratory approach and engages with a range of interconnected spatial variables. Using Space Syntax angular segment analysis at local and global radii, six time slices (2002–2025) are analysed for integration, choice, and intelligibility. A slope-range index from SRTM data quantifies terrain engagement at the segment level. The relationship between terrain and configuration is then interrogated at the level of individual access network segments through bivariate correlation, multivariate regression, and spatial autocorrelation diagnostics. The findings illustrate how the 2017 major influx marks a configurational rupture: local and global integration cores diverge, global choice axes reorient, and intelligibility falls significantly by 2025. Terrain associations with syntactic measures are statistically detectable but substantively negligible: elevation and slope add negligible explanatory power once segment length, building density, water, and road density are controlled for, and model residuals remain strongly spatially autocorrelated, so terrain effects are interpreted as exploratory rather than causal. The study shows how topography constrains but does not deterministically shape the network's evolution under crisis conditions. The findings also suggest that as flatter terrain became saturated first, expansion increasingly encroached into steeper, more topographically challenging areas. Presenting a novel exploration of the dynamics between topography and configurational morphogenesis in a significantly large settlement, this study offers insights to inform more spatially grounded and contextually tailored upgrading interventions in displacement contexts.

Keywords: Informal Urbanism; Morphogenesis; Urban Morphology; Mapping; Space Syntax, Informal Settlement

1. Introduction

Forms of urbanity generally emerge from ongoing interactions between people and the built environment. While these interactions are often mediated by formal, top-down planning frameworks, urban informality remains a critical mode of producing and adapting places across much of the Global South. Amid rapid urbanisation and population growth, urban informality has become integral to the making, unmaking, and remaking of places, particularly in the context of what is considered the Global South (Dovey, 2019; Dovey & King, 2012; Kamalipour, 2022; Kamalipour & Peimani, 2025).

The scholarship on informal urbanism is diverse; in part, it celebrates resilience, resourcefulness, and vibrant social and spatial structures (Parthasarathy, 2015; Roy, 2015). The scholarship also puts emphasis on poverty, inadequate infrastructure, health, precarious tenure, legal exclusion and socio-spatial segregation (Corburn & Sverdlik, 2019; Fernandes, 2011;

Huchzermeyer & Karam, 2006; UN-Habitat, 2016, 2022, 2024). Informal settlements often remain absent from official maps (Kamalipour & Dovey, 2019; Robinson, 2002), rendering them less visible in policy and more challenging to investigate in scholarship (Kamalipour & Peimani, 2024; Myers, 2011, 2021; Thinh et al., 2026). The limited recognition of these settlements, together with considerable gaps in available data, makes alternative explorations of these settlements particularly important to inform the long-term planning and upgrading strategies.

Despite being often invisible, forms of informality are considered generative. The self-organised spatial logics intrinsic to the formation and adaptation of informal settlements can shape and incrementally transform urban space (Kamalipour, 2023). Home to an estimated one billion people worldwide (UN-Habitat, 2006, 2020), informal settlements constitute a critical form of urbanism. While there is an emerging body of knowledge on informal settlement exploring their typologies, morphologies, and incremental transformations (for instance, see Alegría & Dovey, 2024; Dovey et al., 2020; Kamalipour & Iranmanesh, 2021; McCartney, 2025; Muñoz & Ramos, 2024; Suhartini & Jones, 2023; Thinh & Kamalipour, 2022; Thinh et al., 2023; Thinh et al., 2024), the complexity of certain dynamics such as the ways in which topography interacts with access network configurations over time—particularly under extreme conditions of rapid expansion in emerging refugee settlements—remains understudied. While there is also emerging literature exploring the spatial dynamics of refugee settlements (for instance, see Abu-Aridah & Ligler, 2024; Al-Homoud & Samarah, 2025; Maqusi, 2023; Weigand et al., 2023), their configurational morphogenesis in relation to topography remains underexplored.

Informal settlements often evolve through a range of incremental adaptations and informal codes, some of which have already been outlined in the existing literature (for instance, see Jones, 2019; Kamalipour & Dovey, 2018, 2020; Issah et al., 2026). One of the less explored issues in this scholarship concerns the moments when these settlements experience sudden population shocks, such as mass displacement events. The impacts of such events on the transformation of informal settlements, and the potential disruptions to their underlying spatial logics, remain underexplored. Kutupalong, in Cox's Bazar, Bangladesh, is one of the largest refugee camps in the world (UNHCR, 2023) and a critical case where long-term incremental growth (2002–2016) was followed by unprecedented, rapid expansion after the August 2017 influx of Rohingya refugees (Braun et al., 2019; UNHCR, 2023).

This paper explores these issues through a multi-temporal, segment-based Space Syntax analysis of Kutupalong's access network (2002–2025). By combining angular segment measures at local and global radii with a slope-range index derived from SRTM elevation data, along with further secondary data layers such as building density, access network density, and waterways, this paper addresses the following key questions concerning configurational change and terrain influence:

- How has the Kutupalong's access network evolved, in both local and global terms, from incremental growth (2002–2016) to rapid expansion (2017–2025)?
- To what extent has topography enabled or constrained the network's spatial transformations over time?

Informed by extensive spatial analysis, the findings of this study contribute to the emerging scholarship on configurational morphogenesis of the access network by clarifying both the scale of network transformation after the rapid population displacement in 2017 and the potential role of topography. Rather than treating terrain as a deterministic driver, the paper

positions it as one condition within a broader assemblage involving path dependency, density, hydrology, emergency siting, institutional interventions, and residents' everyday adaptations. It further considers ways to foster coherence in fractured access networks, while recognising the agency and adaptive tactics of inhabitants. The study focuses mainly on morphological and configurational exploration. Governance, political dimensions, humanitarian practices, and lived experiences of inhabitants are presented here at a contextual level; therefore, the analysis does not make any claims in regard to socio-political processes of the camp.

The article is structured as follows. Section 2 contains a concise literature review of informal urbanism and incremental morphogenesis. Section 3 presents the research design and methods, beginning with Kutupalong as the critical case and followed by the Space Syntax and GIS workflows. Section 4 reports temporal configurational analyses. Finally, Section 5 concludes with a discussion synthesising how these findings contribute to scholarship on informal morphogenesis, the configurational development of Kutupalong, and the study's limitations and directions for future research.

2. Informal Urbanism and Incremental Morphogenesis

Informal urbanism represents a key mode of urbanisation, particularly in the Global South (UN-Habitat, 2016, 2022). AlSayyad (2004) advocates for understanding informality as a way of life, while Roy (2015) conceptualises it as a mode of regulating and producing space. Informality is, as Harris (2018, p. 278) puts it, an “inevitable context of planning”. As Roy (2005) argues, the state produces informality and its embodied state of exception. Forms of informal urbanism have become integral to how places work, particularly in the context of the Global South (Dovey, 2012; Kamalipour & Peimani, 2025). Care should be taken to distinguish urban informality from poverty and the absence of regulation (Roy, 2009). Generally characterised by self-organised and incremental development, urban informality can be understood as both a product and a process, associated with a range of collective and individual desires and fears (Kamalipour, 2024). Informal urban spaces often emerge as people address critical housing and infrastructure needs that are not addressed—or cannot be addressed—by formal planning, resulting in settlements with distinct morphological, social, and functional characteristics (Silva & Farrall, 2016; Thinh et al., 2025).

Incremental urbanism can be considered a key aspect of urban informality, incorporating piecemeal transformations and gradual adaptations over time (Kamalipour & Dovey, 2018, 2020). Incrementalism, as Simone (2008, pp. 28-29) notes, embodies residents' capacity to build on existing resources and practices to further diversify economies, while also reflecting specific relationships with broader communication and infrastructure networks. Incremental adaptation can be understood as a form of improvisation (Hamdi, 2004; Kamalipour, 2020). Incremental urbanism incorporates generative processes as an adaptive response of residents to dynamic social, economic, and environmental conditions and emerging needs (AlSayyad, 2004; Muñoz & Ramos, 2025). It involves processes of improvisation and negotiation among diverse actors (McFarlane, 2011). Informal settlements typically display unique morphogenic processes characterised by a fairly flexible and adaptive built environment (Iranmanesh & Kamalipour, 2023).

The generative processes underlying the production of urban spaces in the context of informal urbanism often manifest in complex urban morphologies. Informal urban forms evolve through processes of incremental adaptation, informed largely by informal rules or codes (Kamalipour & Dovey, 2018, 2020). The resulting access networks, densities, mixes, types, and public/private interfaces give rise to diverse urban realities that manifest as various forms of

informal settlement (Kamalipour, 2024). The resulting complex urban forms also present significant challenges in terms of providing services and infrastructure for the inhabitants (Ncube, 2025). Access networks within informal settlements are often narrow, labyrinthine, and precariously built, hindering mobility and service delivery, exacerbating social inequities, and increasing vulnerability to environmental hazards such as flooding and landslides (Hussainzad & Gou, 2024).

Many informal settlements exist in a state of uncertainty, which complicates residents' claims to urban rights and access to essential services such as water, sanitation, and electricity (Gagakuma, 2026; Jones, 2017; Kamalipour & Peimani, 2021). From the perspective of opportunities, amenities, and infrastructure, and despite the generative potentials of informal processes, informal urban forms also have the potential to generate spaces of exclusion from the larger urban network, as well as conditions of marginalisation and infrastructural inequity (Meagher, 2021; Soliman, 2021). While informal rules or codes rely on negotiation and shared consensus, their proscriptive nature does not appear sufficient to prevent slum conditions from emerging (Kamalipour & Dovey, 2020; Thinh & Kamalipour, 2022). Recent scholarship on the topic advocates participatory and inclusive approaches to address these challenges, highlighting the importance of resident-driven mapping, participatory governance, and adaptive urban strategies (Al-Hagla, 2024; Mottelson & Wolff, 2025). The complexity of dynamics such as the relationships between topography and access network configurations over time, particularly under conditions of rapid, shock-driven expansion in refugee settlements, remains understudied, and their configurational morphogenesis in relation to topography remains underexplored. This is a relevant issue in this discourse because rapid urban growth in vulnerable settings can extend into hazard-prone land when access to safe and serviced land is limited (Mitchell et al., 2015). The analyses of this study primarily focus on the morphological and configurational dimensions of this broader issue.

3. Research Design and Methods

3.1. Case Study: Kutupalong Settlement

The research presented in this paper adopts what Flyvbjerg (2004) refers to as an “information-oriented” approach to case study selection, focusing on the Kutupalong refugee camp as a “critical” case in relation to the study topic. The Kutupalong refugee camp, located in Cox's Bazar district of Bangladesh (also referred to as Kutupalong–Balukhali expansion site), is regarded as the world's largest refugee settlement, accommodating the world's largest stateless population (at the time of writing this paper) (UNHCR, 2025a, 2025b). Figure 1 shows the location of the settlement within its broader geographical context. The camp is predominantly housing Rohingya refugees fleeing ethnic persecution from Myanmar (Beyrer & Kamarulzaman, 2017). The built environment of Kutupalong refugee camp can be considered a product of rapid, large-scale displacement, having expanded and densified over time as it evolved from a temporary emergency site into a considerably large settlement shaped by ongoing adaptations (Islam et al., 2023). While the camp's expansion initially appeared as a process of incremental development, its transformation into the settlement seen today occurred over a remarkably short period, as illustrated in Figure 2. Kutupalong was originally a small settlement established in the early 1990s. The camp transformed into a considerably large settlement, accommodating approximately one million refugees after the 2017 Rohingya crisis (Braun et al., 2019; Loncar & Cabral, 2022). Since the mass arrival of Rohingya refugees in 2017, the settlement has undergone exponential and mostly unplanned expansion. Analysis by Loncar and Cabral (2022) shows that the urban footprint of the camp more than doubled within just nine months, expanding from 2.01 km² to 5.37 km². Bappa et al. (2022) report a tenfold

increase in human settlements between 2015 and 2021, accompanied by a 74% decrease in forest cover (also see Braun et al., 2019). The rapid and unplanned expansion of the settlement has also contributed to significant environmental issues, such as the decline in forest cover and biodiversity within the camp's vicinity (Bappa et al., 2022; Hasan et al., 2023; K. J. Rashid et al., 2021). In the broader Cox's Bazar context, Islam et al. (2023) characterise the growth of Rohingya settlement as a shock-driven spatial transition that extends beyond the camp itself and understanding its processes might provide regional insight.



Figure 1. The case study location within its broader geographical context. Satellite images: Google Earth.

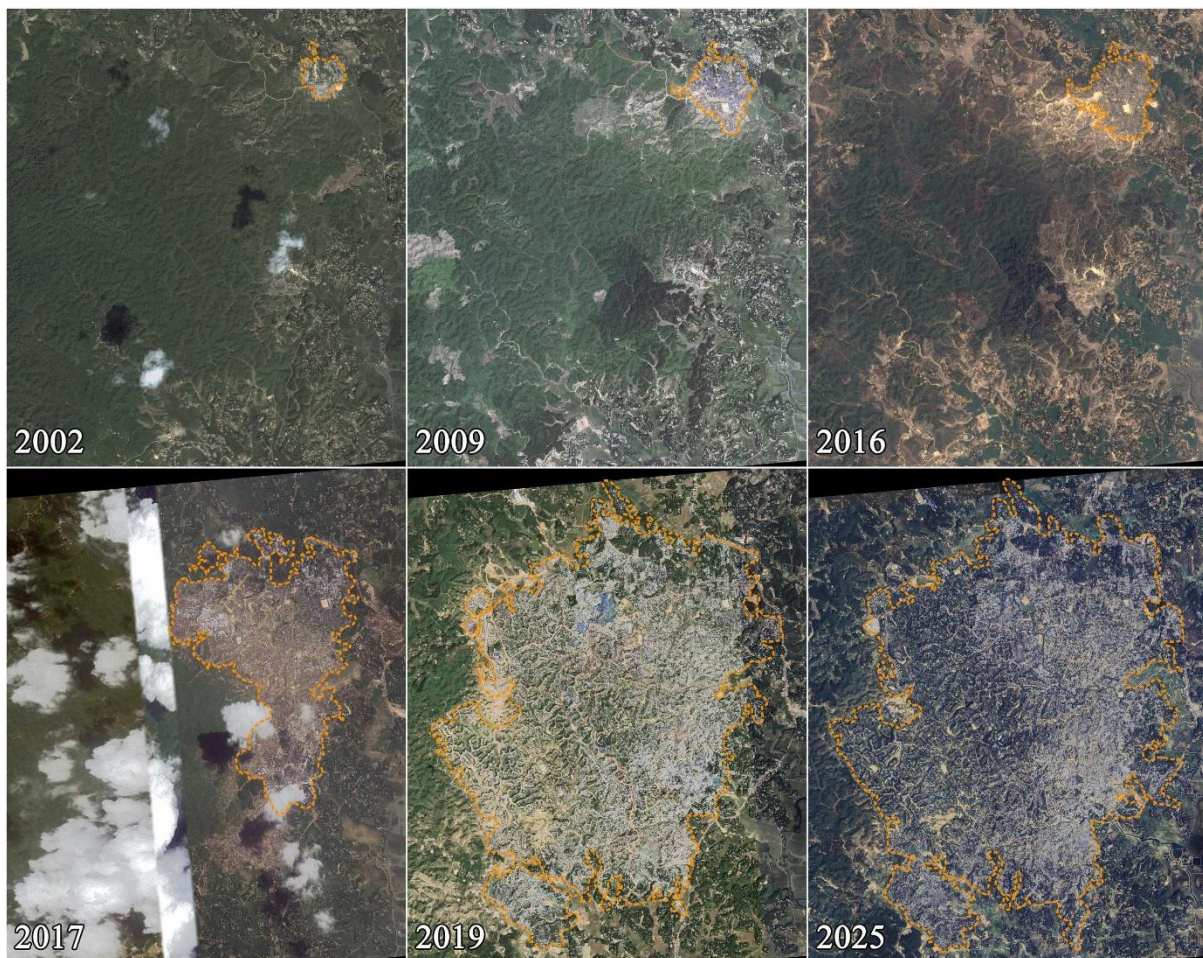


Figure 2. The emergence and transformation of the case study area over time. Satellite images: Google Earth.

The urban morphology of Kutupalong reflects characteristics commonly associated with informal urbanism. These characteristics include self-organised patterns, densification, incremental transformations, and significant socio-spatial stratifications (see Karunaratne, 2023). The general growth pattern of the settlement does not seem to follow any urban planning guidelines or structured policies, resulting in complex socio-spatial configurations (Weigand et al., 2023). This has contributed to many vulnerabilities to natural hazards such as landslides and flooding (S. Hossain et al., 2024). Health and socio-economic conditions within the camp add further complexities, reflected in the particularly challenging humanitarian conditions faced by refugees (Ahsan & Christensen, 2024; Alam et al., 2023; Christensen et al., 2020). Limited educational opportunities and socio-economic marginalisation have also been reported to perpetuate cycles of poverty and exclusion (Rahman et al., 2023). Although many institutional efforts are organised to address the environmental, infrastructural, and humanitarian challenges in Kutupalong, these efforts remain inadequate due to the scale and complexity of the crisis (Uddin, 2025).

The Kutupalong refugee camp also faces many deeply rooted socio-spatial and health-related challenges. Issues such as mental health, psychological distress, malnutrition, chronic idleness, the fracturing of families, domestic conflict, and profound uncertainty about the future are reported (Ahsan & Christensen, 2024; Alam et al., 2023; Christensen et al., 2020). Children and women face intersectional forms of discrimination, which are heightened by limited access to basic education, exploitation, and violence (Hossain et al., 2026; Rahman et al., 2023). Overall, these interconnected issues reinforce patterns of marginalisation and “bare life” (Hossain et al., 2026) that are shaped by both juridico-political exclusion and everyday struggles for dignity, security, and hope (Palit et al., 2022).

The Kutupalong settlement is situated on steep, deforested hillsides, characterised by fragmented and often challenging networks of paths and routes. Kamal et al. (2023) describe how refugees have built dense clusters of shelters along hilltops, slopes, and valley floors to meet the need for shelter. The access networks in Kutupalong typically consist of narrow footpaths cut into slopes. These paths are vulnerable to monsoon rains and have contributed to repeated slope failures and loss of life (S. Hossain et al., 2024). Providing a better understanding of the settlement’s incremental adaptation processes through the lens of urban informality offers valuable insights for developing more contextually sensitive and spatially grounded design, planning, and policy interventions that can more effectively address ongoing challenges and make potential contributions to the ways that might help improve the spatial conditions of the settlement.

3.2. Space Syntax Analysis of Access Networks

Space Syntax represents a set of evidence-based theories grounded in an analytical framework for understanding the spatial configuration of the built environment (Hillier & Hanson, 1984; Karimi, 2012). In urban environments, Space Syntax offers quantitative measures of how the spatial layout of built forms influences—and is influenced by—movement patterns, accessibility, and social interaction (Hillier, 1996a, 1996b, 1999). Space Syntax has evolved to incorporate diverse measures that capture both local and global properties of spatial networks, making it a strong tool in exploring the spatiality of informal networks (Cutini et al., 2019; Hillier et al., 2000; Karimi & Parham, 2012). The Space Syntax theory is grounded in two concepts: first, the spatial structures are not mere background to human presence and are integral parts of it (mutual relationship), and second, built environments cannot be fully

understood in isolation and must be considered as a part of the larger spatial network (Hillier, 2012; Karimi, 2012).

In this study, Space Syntax is used to analyse the access network of Kutupalong refugee camp through three primary measures: integration, choice, and intelligibility. Integration reflects the degree to which a given segment is accessible from all other segments within the network (Hillier, 1996b; Hillier & Iida, 2005). The Space Syntax literature provides strong evidence for the relationship between potential pedestrian movements and integration (Askarizad et al., 2024; Hillier & Iida, 2005; Sharmin & Kamruzzaman, 2018). Drawing on the idea of co-presence, the integration has also been shown to be a significant contributor to social interactions and consequently the development of microeconomy (Hillier, 1996a; van Nes & Yamu, 2017).

Choice measures (also known as a function of through-movement or betweenness) the likelihood of a segment being part of the shortest paths between all pairs of potential origin-destination pairs (Turner, 2007). Intelligibility represents the legibility of the global network from local configurational features. In this study, intelligibility is presented as the correlation coefficient between local and global integration values (Bafna, 2003; Karimi, 2018; Long & Baran, 2012). Space Syntax analyses were conducted on angular segment maps, where the street network is divided into the smallest possible line segments between intersections, and the cost of movement is modelled based on the angular change rather than metric distance (M. Rashid, 2019; Turner, 2007; van Nes & Yamu, 2021). The existing body of literature indicates that angular analysis represents a more accurate model for exploring pedestrian behaviour, particularly in informal and irregular urban morphologies (Karimi, 2018; Turner, 2007). The analyses are conducted on two scales representing global ($R=n$) and local ($R=400m$) measures. These proxies represent the extent to which nodes are accounted for in relation to one another.

Space Syntax has an established precedent in the analysis of informal settlements. The method offers an analytical means to explore and interpret the dynamic and incremental evolution of spatial configurations that emerge in the absence of formal planning (Iranmanesh & Kamalipour, 2023, 2026; Karimi & Parham, 2012; Tufek-Memisevic, 2023). The existing literature indicates that the configurational structures of informal settlements often display underlying spatial logics shaped by patterns of accessibility, visibility, and movement potential (Hillier et al., 2000; Karimi, 2018; Oviedo et al., 2021). Iranmanesh and Kamalipour's (2023) syntactic analysis shows that informal settlements display identifiable configurational patterns (also see Iranmanesh & Kamalipour, 2026). Integration and Choice cores can represent how particular routes act as configurational spines within access networks.

Beyond diagnosis, previous studies show how syntax-based approaches can model the effects of incremental transformations of access networks (Iranmanesh & Kamalipour, 2023, 2026). Therefore, understanding the evolution of urban forms from the perspective of configurational structures can provide evidence for interventions aiming to upgrade these settlements without undermining established social and spatial patterns (Hillier et al., 2000; Iranmanesh & Kamalipour, 2026; Karimi & Parham, 2012). In this way, Space Syntax provides not only a lens for analysing informality but also a practical toolkit for shaping its evolution in ways that can improve accessibility, resilience, and spatial equity.

In contexts like Kutupalong, where the network emerges through incremental development (and partially rapid in this case), these measures can offer crucial insights into the relationship between morphology, accessibility, and resilience. By correlating spatial metrics where official data is scarce and constantly changing, the method provides an approach grounded in the

existing urban literature that can be utilised for potentially improving and upgrading informal access networks. Such approaches have particular resonance in displacement sites like Kutupalong, where spatial transformations occur rapidly and unpredictably. By situating the study within this body of work, the analysis leverages an established methodology for unpacking the evolving configurational characteristics of informal urbanism and exploring their implications for accessibility, resilience, and social life.

It must be noted that the scope of configurational reading of Space Syntax is rather limited. The measures used here should not be read as direct evidence of social interaction, wayfinding, mobility, or lived experiences. These Space Syntax measures index, based on the evidence from the literature, the configurational conditions and movement potentials generated by the access network. Accordingly, these measures can support spatial affordance and movement hierarchies. While they cannot be considered a replacement for actual observation, in the absence of official data, they can provide grounded insights into the interaction between people and access network (see van Nes & Yamu, 2021). Nevertheless, the socio-political circumstances of the settlement are presented to provide context for the interpretation and are not directly studied as explanatory variables.

3.3. Mapping and GIS

The study is exploratory in nature, employing extensive mapping and drawing on secondary data sources. It maps the incremental development of Kutupalong refugee settlement over time, focusing on the main Northern cluster of camps and using a series of temporal access network maps that were manually generated based on Google Earth historic imagery. These maps were also cross-referenced with Open Street Map (OSM) datasets. The data has been analysed and curated using a Geographic Information System (QGIS). Incremental maps were created for the years 2002, 2009, 2016, 2017, 2019, and 2025. The logic behind the selection of these temporal sequences lies in the key moments of the settlement's development. Between 2002, 2009, and 2016, growth was minimal, with relatively slow and spatially limited expansion. In fact, the growth between 2009 and 2016 was so minimal that including another timeframe would not have been significant. By contrast, the period from 2016 to 2019 witnessed a rapid and extensive transformation driven by the large-scale influx of refugees in 2017. Consequently, equal time intervals were not adopted, as they would not have captured the significant morphological shift during this critical expansion phase (Figure 3).

One of the initial intentions of the study was to explore the impact of topography on the structure of the informal settlement. Accordingly, all data layers were explored in their correlations with the topography and level differences in different time frames. Secondary spatial datasets included a topography raster (NASA SRTM), building footprints (based on OSM and manually completed), and waterway networks (OSM). As part of the analysis, the level difference per metre (range) for all street segments was calculated in QGIS to explore potential topographic constraints on accessibility. Space Syntax analyses—measuring integration, choice, and intelligibility—were conducted for each mapped period using angular segment analysis.

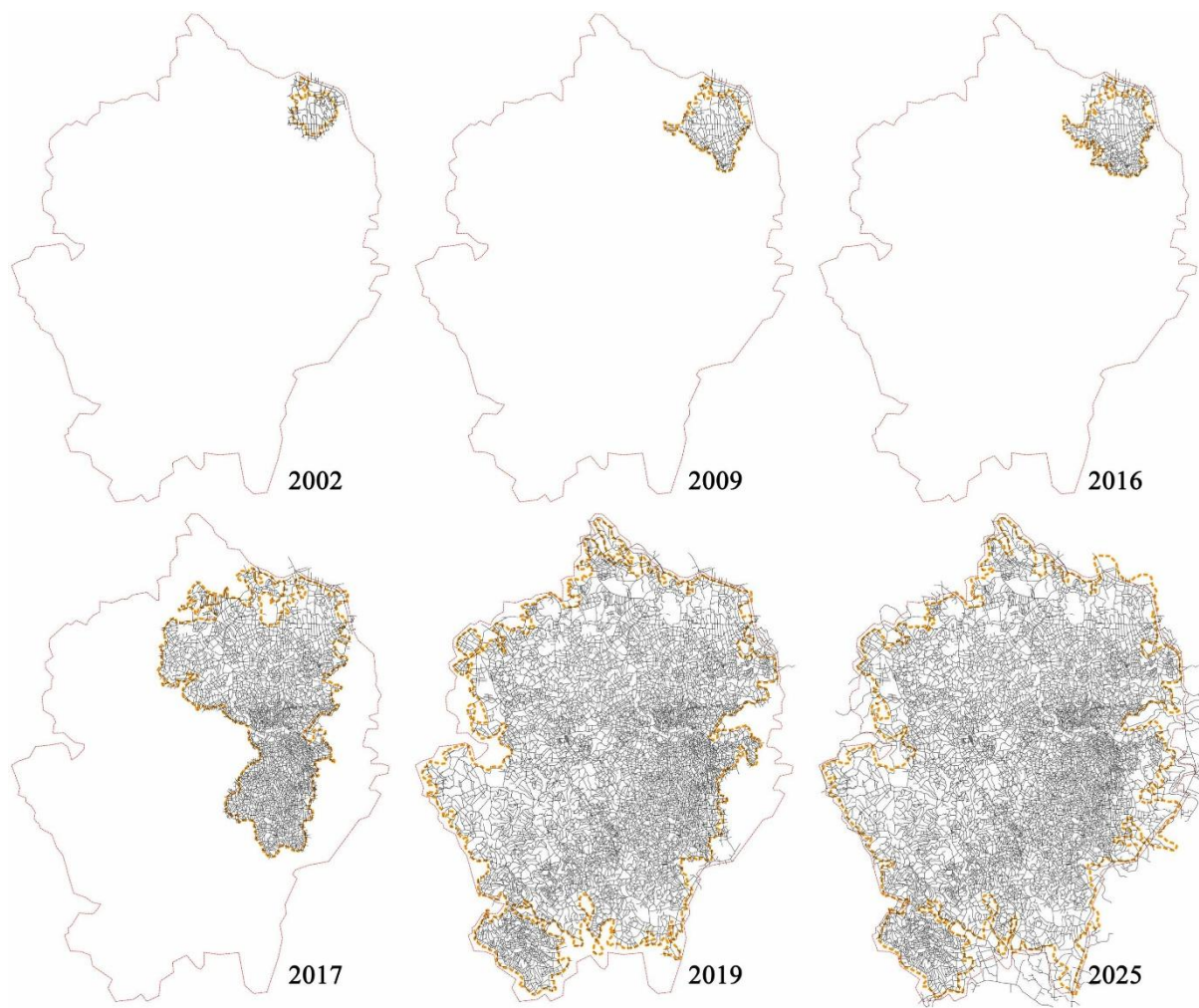


Figure 3. The evolution of the access network development in the case study area.

4. Analysis and Results

4.1. The Processes of Centrality

The integration analysis shows a notable transformation of centrality. During the incremental expansion of the camp southwards, the integration core gradually moves. The local and global integration cores overlap during these stages (which is normally expected; see Al-Sayed et al., 2012; Barthélemy et al., 2013; Hillier et al., 1993). However, there is a significant rupture in the integration core during the rapid expansion of 2017. During this period, the spatial positions of the local and global integration cores are separate (Figure 4). The same rupture in the global core occurs once more during a short period between 2017 and 2019. Meanwhile, the local core remained relatively stationary, suggesting greater resilience. The local cores represent some accessible local nuclei in the settlement. While the access network expands, new local cores emerge, but one often remains as a central local core. While the local integration cores appear similar to many others in the world, the integration core exhibits a seemingly chaotic pattern, which is not commonly observed in self-organised access networks. A similar rupture can be observed with regard to the global choice core. While the choice core expands on the same north-south axis between 2002 and 2017, the rapid post-2017 expansion completely changes the choice cores into a different set of axes (Figure 5). This is a relatively uncommon occurrence, as the orientation and significance of the access network elements with high choice

value tend to be persistent and resilient. The local choice cores represent connections between different parts of the settlements. In this case, many of the access network elements with high choice value pass over wetlands and rivers through makeshift bridges. The identification of these highly in-between spaces is critical for the monsoon season, when the mobility of large numbers across camps becomes a critical necessity.

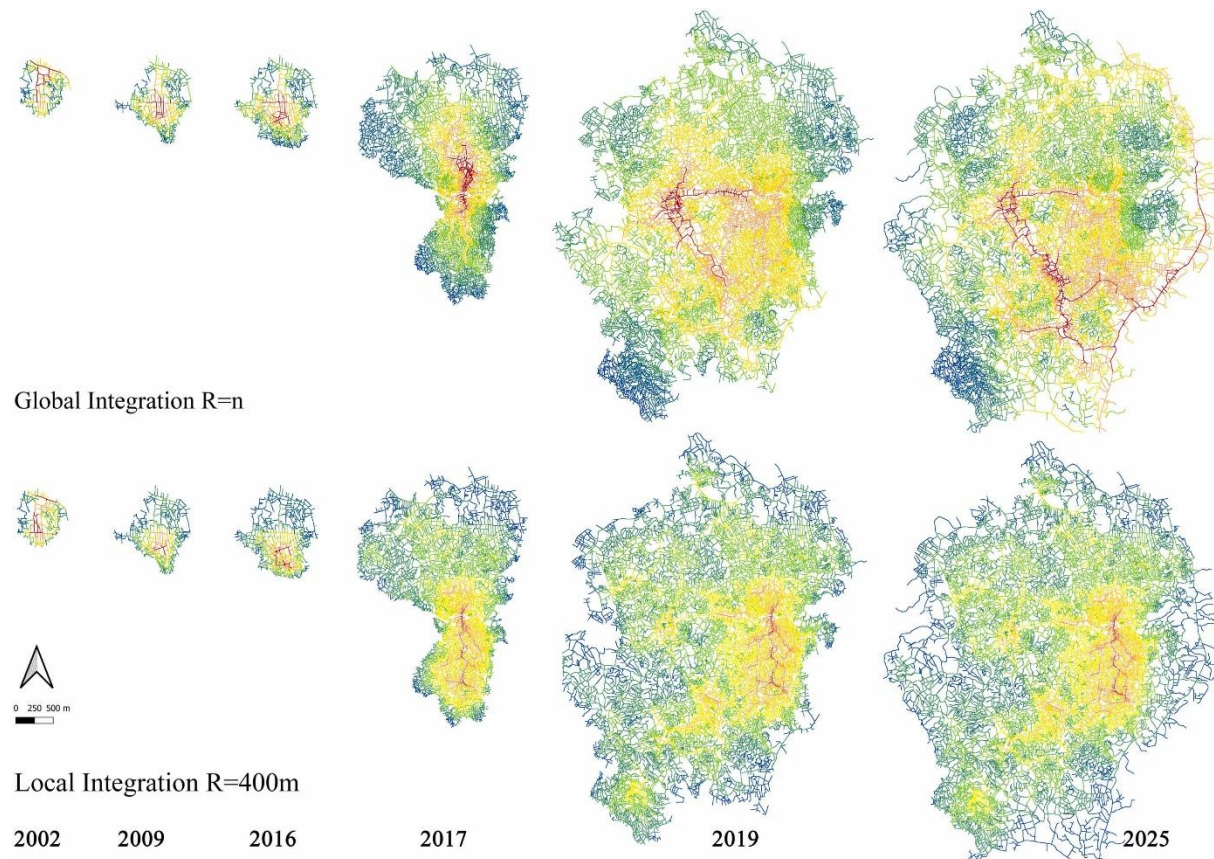


Figure 4. The incremental evolution of global and local integration of the access network of Kutupalong (2002-2025).

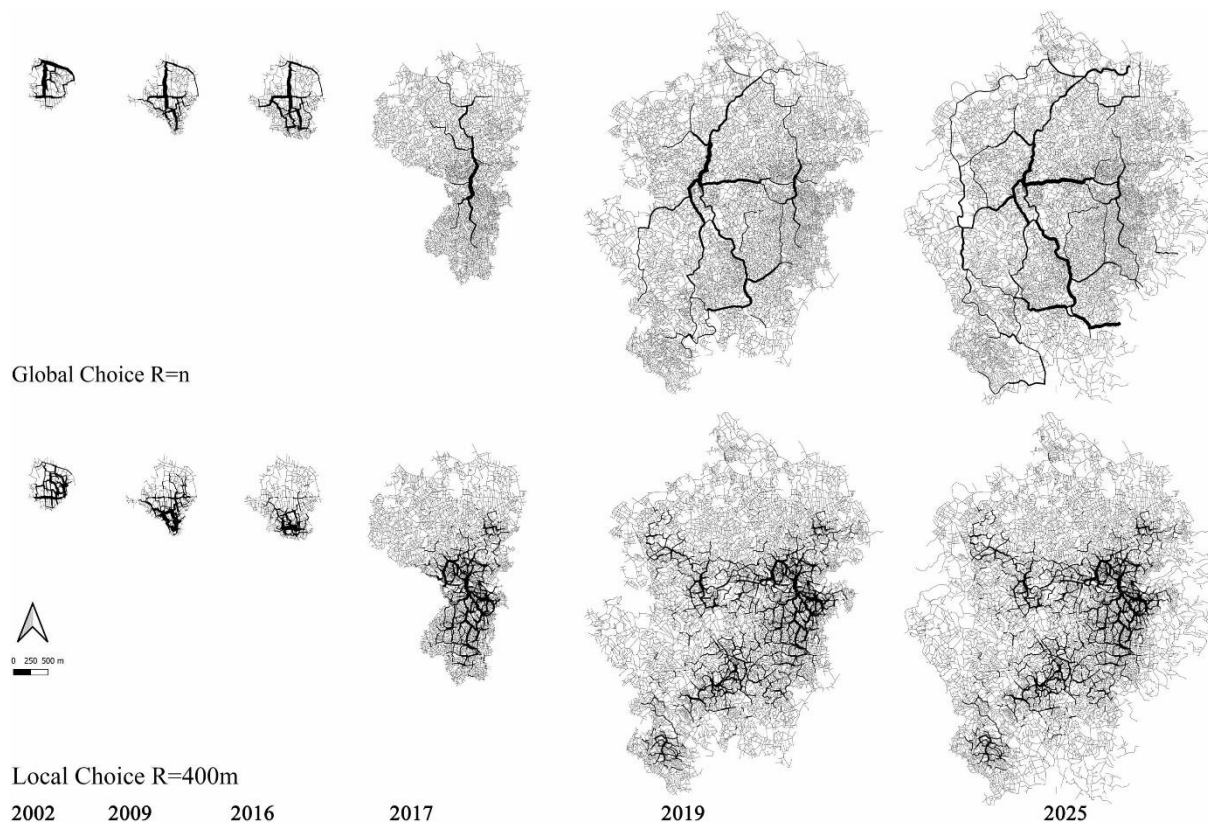


Figure 5. The incremental evolution of global and local choice of access network of Kutupalong (2002-2025).

The statistical exploration of the data presented in Figures 4 and 5 supports these interpretations. The intelligibility analysis—expressed here as the Pearson correlation coefficient between local and global integration indicates a significant decline in spatial coherence of Kutupalong’s access network (Table 1). In the earliest recorded period (2002), the correlation (legibility) was high ($r = 0.931$, $p < 0.01$), indicating a highly intelligible network where local configurational values were strongly aligned with the global spatial structure. This pattern persisted through 2009 ($r = 0.928$) and 2016 ($r = 0.899$), reflecting a relatively compact, spatially coherent settlement morphology during the settlement’s early and pre-crisis phases. High intelligibility in these stages suggests a configurationally legible network structure, consistent with findings in relatively smaller informal settlements where spatial growth generally remains closely tied to a limited set of primary access routes (for different instances supporting this argument, see Fan et al., 2022; Iranmanesh & Kamalipour, 2023; Kamalipour & Iranmanesh, 2021; Long & Baran, 2012).

A noticeable decline can be seen after 2017, when intelligibility falls to $r = 0.824$ in 2017 and drops to $r = 0.726$ in 2019. This decline reflects the rapid, unplanned expansion that accompanied the humanitarian crisis; this process could be associated with a growing configurational fragmentation of the access network. By 2025, intelligibility had fallen to $r = 0.568$, the lowest in the dataset, indicating a substantial separation between local and global spatial structures. This decline suggests that the settlement’s growth trajectory has resulted in a network where the accessibility of local routes becomes gradually misaligned with global connectivity. It could be argued that the temporal sequence in Kutupalong aligns with broader observations suggesting that accelerated expansion in informal settlements tends to erode network intelligibility over time.

Table 1. Temporal evolution of intelligibility presented as the correlation coefficient (Pearson) between global (R=n) and local (R=400m) integration.

YEAR			Local integration at R=400m (angular)
2002	Global integration (angular)	Pearson Correlation	.931**
		Sig. (2-tailed)	0.000
2009	Global integration (angular)	Pearson Correlation	.928**
		Sig. (2-tailed)	0.000
2016	Global integration (angular)	Pearson Correlation	.899**
		Sig. (2-tailed)	0.000
2017	Global integration (angular)	Pearson Correlation	.824**
		Sig. (2-tailed)	0.000
2019	Global integration (angular)	Pearson Correlation	.726**
		Sig. (2-tailed)	0.000
2025	Global integration (angular)	Pearson Correlation	.568**
		Sig. (2-tailed)	0.000

** . Correlation is significant at the 0.01 level (2-tailed).

4.2. Topography and Incremental Genesis of Forms and Networks

A key ambition of this study was to explore how topography has enabled or constrained the network's spatial transformations over time within the context of informal urbanism. To this end, the study used the NASA SRTM raster file (with a resolution of 30m). The topography ranges between -2 and +34 metres above sea level. For initial screening, Kernel Density Estimation (KDE: heatmap) with the same bandwidth was generated for all secondary variables (see Figure 6). The special circumstances of the settlements create a presupposition that the topography might be one of the major drivers behind the formation and transformation of the access network.

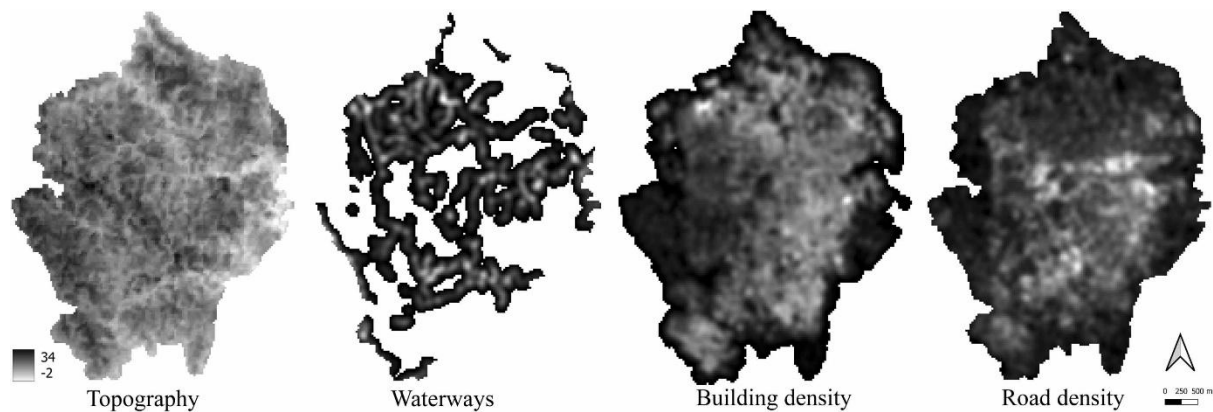


Figure 6. Topography and KDE of secondary data layers.

In order to explore the relationship between the topography and other variables, all secondary layers were aggregated onto the 2025 segment map, yielding one observation per segment. Accordingly, the topography, building-density, water, and road-density rasters were summarised along each segment (zonal statistics). The topography was explored via per-segment mean elevation, elevation range, absolute elevation difference, average slope, and elevation standard deviation.

Three complementary procedures were applied to explore the relationship among these layers. First, Pearson correlations were computed between each measure (global and local choice, global and local integration) and each terrain variable. These correlations are reported as screening tools, and the interpretation is based on effect size rather than on the p-value alone (see Wasserstein & Lazar, 2016). Second, to isolate the unique contribution of terrain from that of the other morphological variables, a hierarchical (nested) sequence of ordinary least squares (OLS) regression models was estimated for each measure (Cohen et al., 2003). The purpose of the nested modelling strategy was not to produce a comprehensive predictive model, but to test whether terrain contributes any additional explanatory power after accounting for segment geometry, built density, hydrological presence, and road-network density. Model 1 contained the terrain predictors alone (mean elevation and slope); Model 2 contained only the controls (segment length, building density, water, and road density); and Model 3 contained the controls plus the terrain predictors. Because Models 2 and 3 are nested and Model 3 simply adds elevation and slope to the identical control set, the difference in their coefficients of determination, $\Delta R^2 = R^2(\text{Model 3}) - R^2(\text{Model 2})$, measures precisely the share of variance that terrain explains over and above what the controls already account for. Any variance that terrain shares with, for instance, building density is absorbed by the controls in Model 2 and cannot be re-credited to terrain, so ΔR^2 captures a unique increment of the terrain. The significance of the model was assessed with a partial F-test. A supplementary sensitivity model (Model 4) added elevation range and absolute elevation difference to test the robustness of this increment. Variance inflation factors (VIF) were inspected for every predictor, with values above 5 treated as a concern and above 10 as serious, to verify that coefficients were not distorted by multicollinearity (see O'Brien, 2007). Third, because spatial data might violate the independence assumption of OLS, global Moran's I ($k = 8$ nearest neighbours, 199 permutations) was computed both for each variable and for the residuals of the controls-plus-terrain models, to test whether unmodelled spatial structure remained. Where residual autocorrelation persists, the regression results are interpreted as exploratory rather than as estimates of independent causal effects. Although several coefficients reached very low p-values, this reflected the large number of non-independent raster cells rather than any meaningful relationship, and the associations themselves were uniformly weak ($|R| < 0.27$). To place interpretation on firmer ground, the analysis was repeated at the level of the individual access-network segment, which is the genuine unit of Space Syntax analysis. The segment-level results, summarised in Table 2, confirm that terrain is statistically detectable but substantively limited as a predictor of configurational structure, and they are interpreted here primarily through effect size rather than statistical significance.

At the segment level (see Table 2), the bivariate associations between mean values and Space Syntax measures are relatively weak. Global choice (Pearson $r = -0.030$) and local choice ($r = 0.016$) are not related to elevation. Local integration is marginal ($r = 0.051$), and global integration shows the strongest, but still weak association ($r = -0.116$). These correlations correspond to shared variance of well below two per cent, and coefficients of this size are treated here as trivial and not interpreted substantively, irrespective of their p-values. Naturally, the analysis is capable of showing a genuine relationship with the terrain in regard to the waterways. By contrast, the control variables relate to configuration far more strongly than the terrain does. In this regard, building density and road density are the dominant variables correlating with local integration ($r \approx 0.50$ and 0.56).

The multivariate models highlight the same outcome. Adding mean elevation and slope to the model that already contains segment length, building density, water, and road density, the gain in explanatory power is negligible across all four Space Syntax measures (Table 2: the

In order to provide a more detailed reading into the role of topography, the study further explored the local range of level differences. For this purpose, a standardised range per unit of measurement was established for all map segments (Table 3). This index shows the spatial distribution of the range of level differences (as opposed to mere topography). This step was repeated for all six timeframes. The temporal analysis of level difference per metre across Kutupalong's access network shows a significant upward trend in average slope values over the settlement's development history. In the earliest phase (2002), the mean level difference was relatively low at 0.0381 (3.8 millimetres per metre of access network), with a narrow standard deviation ($SD = 0.0813$), reflecting the small scale of the settlement's relatively accessible terrain. The range incrementally increases through 2009 (0.0401) and 2016 (0.0417), suggesting that early development occurred primarily in flatter areas with limited topographic constraints—consistent with a commonly observed tendency for initial settlement to prioritise the most accessible and buildable land.

A notable change emerges after the 2017 influx, when the mean slope value rises sharply to 0.0524, accompanied by a significant increase in variability ($SD = 0.1355$). By 2019, this trend continues (mean = 0.0549), stabilising slightly in 2025 (0.0546). The higher means and standard deviations suggest that as flatter terrain became saturated, expansion increasingly encroached into steeper, more topographically challenging areas. This aligns with findings from other high-density informal contexts, where rapid, unplanned growth pushes settlement into marginal lands—such as slopes, floodplains, or other hazardous terrain. This shift seems to occur due to limited space and pressing demographic pressures (see instances in Kühnl et al., 2023; Shand & Ndezi, 2025; World Bank, 2009; Wurm et al., 2023). The post-2017 pattern in Kutupalong reflects this dynamic, where the relationship between built forms and level differences becomes less stable.

It must be noted that while the data show a statistically significant upward shift in slope engagement after 2017, the magnitude of this change is relatively modest compared to the scale of the settlement's morphological transformation. The overall mean for the entire period (0.0539) suggests that topography is a contributory but not dominant driver of network formation in Kutupalong. This nuance is important: although steeper terrain increasingly features in the network as expansion progresses, other spatial, social, and organisational factors—such as proximity to services, social clustering, and the path dependency of earlier routes—likely exert a stronger influence on network genesis (Hillier, 2009; Netto, 2016). In this sense, the Kutupalong case supports the argument that in high-pressure, crisis-driven informal urbanism, topography contributes to shaping but does not dictate spatial configuration, becoming more relevant only once accessible terrain is exhausted.

Table 3. Temporal evolution of level difference range throughout the access network per unit metres.

YEAR	Mean	N	Std. Deviation
2002	.0381	884	.0813112
2009	.0401	2044	.0947404
2016	.0417	3142	.1043109
2017	.0524	24032	.1355352
2019	.0549	66398	.1474248
2025	.0546	69342	.1468913
Total	.0539	165842	.1440291

5. Discussion

The findings of this study can be interpreted in relation to three apparent gaps in the literature. First, there is rather limited use of multivariate, multi-temporal configurational analysis in contexts of crisis-driven expansion. Second, while many studies have explored different aspects of the case of Kutupalong (for instance, see Chowdhury et al., 2025; Hasan et al., 2023; Hossain et al., 2026; Kamal et al., 2023; Kuligowski et al., 2025; Mitra et al., 2025), its configurational morphogenesis over time as a long-term displacement settlement with informal characteristics remains underexplored. Third, there is relative uncertainty regarding the role of topography in the formation of informal settlements (in particular) and the morphogenesis of urban forms (in general) (for examples of arguments related to Space Syntax and topography, see Asami et al., 2003; Greenberg et al., 2020; Hillier & Penn, 2004; Ratti, 2004, 2005).

Before 2017, Kutupalong's integration core shifted coherently as the settlement expanded southward, with local and global cores being relatively in the same location. After 2017, the separation of local and global cores and the reconfiguration of global choice into new axes suggest a break in path dependency: movement potentials at the settlement scale no longer grow out of earlier established local structures (Al-Sayed et al., 2012). Such a rapid reorientation is rare (for instance, see discussions in Barthelemy et al., 2013; Iranmanesh & Kamalipour, 2023; Kirkley et al., 2018); this highlights how shock-related growth can overwrite emergent hierarchies in incremental networks. This is partially in contrast with some existing studies where the development of informality was more gradual and not sudden (see Hillier et al., 2000; Iranmanesh & Kamalipour, 2023; Jones, 2019; Kamalipour & Iranmanesh, 2021).

What is more, the related literature indicates that high intelligibility is associated with easier wayfinding, stronger alignment between everyday movement and global structure, and higher co-presence and social interaction (Bafna, 2003; Long & Baran, 2012; Peponis, 2024). In the case of Kutupalong, the continuous decline in intelligibility from 2002 to 2025 suggests that local cues (what residents see and navigate day to day) increasingly diverge from the global structure of the settlement's access network. It must be noted that this decline is best read as configurational evidence of reduced correspondence between local and global network structure, rather than as direct proof of social fragmentation which requires further studies. This could also be interpreted within the context of this particular case; disrupted networks may be harder to navigate for outsiders and first responders, may increase travel-time uncertainty, and may exacerbate inequalities between better-connected central clusters and peripheral enclaves. Such consequences, however, are not produced by network geometry alone. Kutupalong cannot simply be considered an entirely self-organising informal settlement as certain governance and humanitarian factors are at play. For instance, there are Refugee Relief and Repatriation Commissioner and Camp-in-Charge structures, humanitarian agencies, and security actors (Manzur & Prova, 2023). Therefore, it is argued that some of the placement of shelters, services, roads, and drainage is conditioned by those bodies (Manzur & Prova, 2023). Recent work also shows that mobility and hazard exposure in these camps are shaped by restrictions on durable infrastructure, fencing, and securitisation as much as by terrain (Rafa, 2026). The access network analysed here is therefore one layer within a broader socio-political assemblage: its configuration structures movement potentials, but those potentials may be affected by institutional rules and everyday practices. These findings can also connect Kutupalong to broader debates on humanitarian urbanism and informal urbanisation, where emergency settlements are negotiated as urban informality while remaining governed through some provisional, restrictive, and formal processes (see Abuawad & Di Raimo, 2025). These

conditions are noted here to support interpretation rather than to explain or indicate causality in regard to the observed morphological changes; the study does not empirically investigate governance, political, or lived-social mechanisms. Accordingly, the post-2017 configurational rupture is not only a morphological transformation but could also be interpreted as an expression of infrastructural precarity under long-term displacement. The finding aligns with the observed fragmentation of the post-2017 network and the proliferation of seemingly ad hoc crossings over wetlands and rivers—segments with high local choice that become critical during monsoon but are structurally vulnerable.

Topography is frequently mentioned in humanitarian, hazard-related, and risk management discussions related to Kutupalong (A. Hossain et al., 2024; S. Hossain et al., 2024; Kamal et al., 2023). However, the relationship between topography and the rapid morphological development of the settlement has remained underexplored. Despite steep, erodible terrain, the present segment-level analysis indicates that elevation and slope exert only a marginal independent influence on configuration. Once segment length, building density, water, and road density are controlled for, terrain cannot be considered a strong predictor of configurational measures. The strong, persistent spatial autocorrelation of the model residuals means that even these small associations cannot be read as independent causal effects. The configuration of the network is thus structured far more by the built fabric and the network's own topology than by the underlying terrain.

The trend in segment-level slope range (mean and variance increasing after 2017) indicates that as flatter land reaches saturation, expansion extends into less favourable/safe terrain. Thus, while early growth in Kutupalong was concentrated in low-slope, more buildable terrain, as these areas became constrained, new growth began to extend into steeper hillsides. This can be considered in line with broader findings that land scarcity and exclusion from formal structures can play a role in changing the pattern of settlement growth into marginal, hazard-prone sites, including steep slopes and riverbanks (also see Kühnl et al., 2023; Shand & Ndezi, 2025; World Bank, 2009; Wurm et al., 2023; Mitchell et al., 2015). In the context of the Cox's Bazar region, Islam et al. (2023) show that Rohingya settlement growth constituted a broader spatial transition rather than an isolated camp-level change. Yet, the extent of the topographic shift observed here is small relative to the configurational changes traced by Space Syntax. The present analysis therefore supports a narrower conclusion: while terrain may inform a range of possibilities, it may not independently explain the morphogenesis of the network. Therefore, factors such as social, political, and temporal dynamics, rapid displacement, emergency siting, and institutional interventions may also play a role in the morphogenesis of the access network. This caution is broadly consistent with recent work showing that informal-settlement upgrading approaches are highly dependent on local spatial and institutional contexts (García Fermín, 2024).

6. Conclusion

This study set out to explore how the configurational properties of the access network evolved through phases of gradual, incremental accretion, as well as crisis-driven, rapid expansion, and how pre-existing topographical conditions may relate to the morphogenesis of Kutupalong, located in Cox's Bazar, Bangladesh. More specifically, the study provides a longitudinal configurational exploration of the transformation of the access network of Kutupalong between 2002 and 2025.

Three notable findings stand out. First, the 2017 influx marks a configurational rupture: global and local integration cores that previously overlapped begin to diverge, and global choice axes

reorient in ways that are unusually volatile for self-organised networks. Second, network intelligibility declines steadily over time, from an exceptionally high, compact pattern to a much weaker correspondence between local and global structure by 2025. These two findings constitute the central contribution of this study. Third, although slope engagement increases after 2017, it appears to be a secondary conditioning factor rather than a primary explanation. The multivariate segment-level analysis shows that the influence of the terrain variables was minimal, especially after controlling for other variables, where regression residuals remained spatially autocorrelated. Accordingly, it could be argued that, in this case, topography may constrain the range of possibilities but does not deterministically drive network formation under crisis conditions, a nuance that the segment-level diagnostics make explicit.

The key contributions of the study presented in this article can be outlined in both methodological and substantive terms. Methodologically, the paper combines multi-temporal mapping (2002–2025), angular segment analysis at local/global radii, and slope-range indexing to unpack how crisis-time growth relates to changes in configurational patterns. The paper also adds nuance to readings of topography in informal morphogenesis, shedding light instead on an assemblage in which terrain is merely one condition among many. The results of the study point to possibilities emerging within a complex and negotiated assemblage, in which terrain is one among multiple interacting conditions, and its role may be influenced by other forces during periods of rapid, shock-driven expansion. Lessons from Kutupalong could inform analyses of other large-scale displacement sites where similar dynamics may unfold but are less well documented.

These conclusions nevertheless should not be interpreted without considering the limitations of the study, particularly in relation to data collection and methodology. For instance, the 30m SRTM raster constrains micro-topographic precision. Some of the secondary data layers, such as building footprints and waterways, were initially extracted from OSM and manually checked; however, these data layers must not be treated as official survey data. It must be noted that there is also the possibility of errors occurring in manual mappings based on satellite imagery. It should also be noted that Space Syntax measures are not a substitute for direct observation or fieldwork; rather, they represent configurational properties of the network whose relationships with movement patterns and social processes have been extensively explored in the literature. It was not possible in this study to integrate what might be considered data on social practices, such as counts and traces, to validate inferred movement potentials. Moreover, the study does not empirically analyse the socio-political dimensions of displacement, humanitarian governance, securitisation, institutional decision-making, or the everyday practices of inhabitants; these are treated only as contextual conditions, and no empirical or causal claims are made about their role in network formation. The study is also relatively limited in its engagement with empirical data on the settlement's everyday dynamics and remains, primarily, a desk-based remote analysis.

Future work could explore higher-resolution raster data in relation to seasonal hydrology, collect data on pedestrian counts and traces across dry and monsoon periods, analyse agent-based routing, and undertake action research to co-produce upgrading scenarios with residents and community representatives, guided by research-informed objectives concerning the access network, which may include improving intelligibility where appropriate, sustaining high-choice bridges, and managing angular detours.

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