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Applications of Topology in Achieving the UN Sustainable Development Goals

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Abstract:

Topology, the mathematical study of properties preserved under continuous deformation, is often seen as purely abstract. However, its principles have significant real-world applications that align closely with the United Nations Sustainable Development Goals (SDGs). This paper explores how topological concepts—such as connectedness, continuity, and invariance—support innovations in areas including sustainable infrastructure, clean energy systems, resilient communication networks, and environmental monitoring. Examples include topology-based optimization in transportation planning (SDG 11: Sustainable Cities), knot theory applications in DNA research for healthcare (SDG 3: Good Health and Well-being), and sensor network layouts for climate monitoring (SDG 13: Climate Action). Case studies highlight how topological reasoning enhances efficiency, reduces resource waste, and fosters resilience in complex systems. By translating abstract mathematical ideas into practical strategies for addressing global challenges, this study demonstrates topology's potential as a bridge between theoretical insight and sustainable development. The findings emphasize the importance of interdisciplinary collaboration, mathematical literacy, and innovative design thinking to achieve the SDGs. This work positions topology not merely as a branch of mathematics but as a versatile, impactful tool for building a more sustainable and equitable future.

Keywords:

Sustainable Development Goals (SDGs), Topology (a branch of Mathematics), Applied Mathematics, Network Optimization, Innovation in Design, Interdisciplinary Problem-Solving

1. INTRODUCTION

Topology, a branch of pure mathematics is concerned with the properties of shapes and spaces that remain unchanged under continuous transformations such as stretching, twisting, or bending, but not tearing. Topology often referred as a 'rubber-sheet geometry', it has extensive

applications in modern science, engineering, and technology. In the 21st century, its relevance extends beyond theory into addressing global challenges, many of which are outlined in the United Nations Sustainable Development Goals (SDGs). By integrating topological concepts into real-world systems, one can design more efficient, resilient, and sustainable solutions. Topology's flexibility and invariance provide robust tools for modeling real-world spaces and networks, aiding in sustainable planning and decision-making. This is how I am here trying to connect a specific branch of Mathematics (which is of course a part of STEAM) with SDGs.
For the readers with some mathematical backgrounds, let us recall some fundamental concepts of topology.

1.1 Some Fundamental Concepts of Topology

- **Continuity:** Function or mapping preserving limits and closeness.

  Traditionally, a function f from a topological space X to a topological space Y is said to be continuous if $f^{-1}(V)$ is open set in X, for every open set V in Y. This means that the "openness" structure, rather than distance or nearness, is preserved by the function. This definition works for spaces where there may be no notion of distance, emphasizing the fundamental role topology plays in modern mathematics.

- **Homeomorphism:** A continuous bijection with a continuous inverse, indicating two shapes share topological properties.

  A homeomorphism is a function $f: X \to Y$ between two topological spaces X and Y if f is bijection, f is continuous and the inverse function f^{-1} is continuous. When such a function exists, the spaces X and Y are said to be homeomorphic, that means they are topologically equivalent or "same" from a topological viewpoint. Homeomorphism preserve all topological properties, so two homeomorphic spaces cannot be distinguished using topological invariants.

  Informally, a homeomorphism can be understood as a continuous deformation (stretching or bending without tearing or gluing) of one space into another. For instance, a square and a circle are homeomorphic, but a sphere and a torus are not.

- **Connectedness:** In topology, connectedness is a fundamental property describing whether a space is "all in one piece" or can be separated into distinct parts.

  A topological space X is said to be connected if it cannot represent as a union of two non-empty, disjoint, open subsets of X. A stronger form is path connectedness, where any two points in the space can be joined by a continuous path within the space. Every path-connected space is connected, but the reverse is not always true. Connectedness captures the idea that the space cannot be split into two "disjoint pieces" without cutting. Path connectedness adds the requirement that there is a "continuous walk" between any two points. This property is central in topology and appears in various important fundamental theorems.

- **Compactness:** In topology, compactness is a property that generalizes the notion of a set being closed and bounded in Euclidean space.

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A topological space X is said to be compact if every open cover has a finite subcover. That is, if you have any collection of open sets whose union includes X, then you can select finitely many of these open sets that still cover X. Roughly speaking Compact spaces have no "holes" or "missing endpoints".

Compact spaces have a very strong property, Compactness is a topological property, that is, invariant under homeomorphisms. Compactness allows generalizing many useful theorems like the Extreme Value Theorem (a continuous function on a compact space attains maximum and minimum values). As an examples, finite sets with any topology are compact, infinite discrete spaces are not compact. This concept plays a crucial role in analysis, topology, and many applied areas of mathematics. In topology, compactness is a property that generalizes the idea of a set being closed and bounded in Euclidean space.

- **Knot Theory:** Knot theory is a branch of topology that studies mathematical knots, which are embeddings of a circle into three-dimensional space. Unlike everyday knots, mathematical knots have no loose ends—they are closed loops that cannot be undone without cutting. Two knots are considered equivalent if one can be smoothly deformed into the other without cutting or passing strands through each other. This equivalence is called an ambient isotopy, a continuous deformation of 3D space mapping one knot onto another.

  Knot theory aims to classify these knots, understand their properties, and distinguish when two knots are the same or different by studying knot diagrams like figure 1. Knot theory is used both in pure mathematics and in practical applications such as DNA structure analysis, physics, and chemistry.

  Essentially, knot theory explores how loops can intertwine in space and classifies these entanglements using topological methods, projecting them into plane diagrams and using special moves called Reidemeister moves to study their equivalence

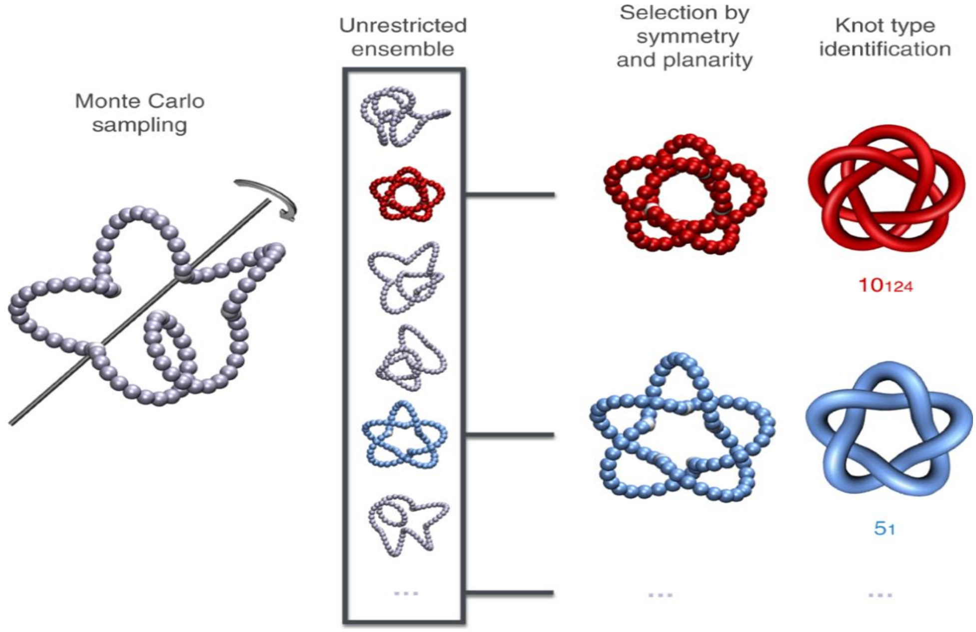

Figure 1: Knot theory identification

1.2 Topology in Everyday Life

- **Knots and Tangles**

Untangling earphones or tying shoelaces directly relates to knot theory. Topological tools study how knots can be transformed, untangled, or classified, with practical implications in surgical suturing and cable management.

- **Clothing and Folding**

Folding a shirt or crumpling paper models how a continuous surface changes shape while preserving topological equivalences. For example, a folded shirt remains "homeomorphic" to an unfolded one, meaning no cuts or tears alter its fundamental structure.

- **Telecommunications Networks**

The internet's topology ensures resilience and efficiency. Routing protocols depend on network connectivity maps, optimizing data flow and handling disruptions without centralized control.

- **Urban Navigation and Maps**

City maps represent road and transit networks, where the exact distances are less important than connectivity. Topological maps highlight how places are linked, vital for route planning, emergency evacuation, and urban design.

- **Food Preparation and Braiding**

The braiding of bread or pastries can be understood through braid theory, a branch of topology related to knot theory, demonstrating how strands intertwine without linkage.

- **Image Processing and Pattern Recognition**

Topological data analysis (TDA) segments and interprets images based on shape invariants rather than pixel intensity alone. This has applications in cancer diagnosis, facial recognition, and autonomous vehicles.

1.3 An Overview of the UN Sustainable Development Goals

The United Nations (UN) launched an ambitious global initiative known as the Sustainable Development Goals (SDGs) in 2015, which reflects a new universal agenda aimed at fostering prosperity while safeguarding the planet. There are total 17 interconnected goals form a blueprint for collective action by countries, international organizations, civil society, and the private sector to achieve a more equitable and sustainable future by the year 2030.

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- **Origins and Purpose**

The SDGs grew out of a global recognition that social, economic, and environmental challenges are deeply intertwined and must be addressed in an integrated manner. They succeeded the Millennium Development Goals (MDGs), extending and deepening the commitment to end poverty and improve living conditions worldwide. Unlike their predecessors, the SDGs emphasize inclusivity and sustainability, underlining the need to balance economic growth with environmental stewardship and social well-being.

- **The 17 Global Goals**

1. **No Poverty:** Striving to eradicate poverty in every form everywhere, this goal addresses the root causes of poverty and advocates for social protection systems and equal rights.
2. **Zero Hunger:** Beyond eradicating hunger, this goal promotes food security, improved nutrition, and sustainable agricultural practices that sustain the environment.
3. **Good Health and Well-being:** Encouraging healthy lives for all, this goal focuses on reducing mortality rates, combating epidemics, and promoting mental health and universal health coverage.
4. **Quality Education:** Inclusive, equitable education and lifelong learning opportunities are imperative for closing gaps in opportunity and empowering individuals.
5. **Gender Equality:** This goal aims to eliminate discrimination and violence against women and girls, empowering them to participate fully in society.
6. **Clean Water and Sanitation:** Sustainable management of water resources and sanitation is targeted to reduce waterborne diseases and protect ecosystems.
7. **Affordable and Clean Energy:** Expanding access to reliable, sustainable energy is seen as essential for economic development and environmental sustainability.
8. **Decent Work and Economic Growth:** Encouraging sustained and inclusive economic growth, productive employment, and decent work for all is fundamental to social stability and improved living standards.
9. **Industry, Innovation, and Infrastructure:** Building resilient infrastructure and fostering innovation are critical for economic progress in a fast-changing world.
10. **Reduced Inequalities:** Addressing disparities within and between countries, this goal promotes social, economic, and political inclusion.
11. **Sustainable Cities and Communities:** As urban populations grow, making cities safe, resilient, and sustainable is an urgent priority.
12. **Responsible Consumption and Production:** Sustainable management of resources and waste reduction are necessary to mitigate environmental degradation.
13. **Climate Action:** Taking urgent steps to combat climate change, build resilience, and integrate policies that address environmental challenges is a defining goal of this era.
14. **Life Below Water:** Conserving marine environments and sustainably using oceans supports biodiversity and livelihoods.
15. **Life on Land:** Protecting terrestrial ecosystems, managing forests, combating desertification, and halting biodiversity loss are essential to sustaining life on Earth.
16. **Peace, Justice, and Strong Institutions:** Promoting peaceful societies, access to justice, and accountable institutions supports stability and development.
17. **Partnerships for the Goals:** The momentum for the SDGs depends on revitalizing global partnerships that mobilize resources, knowledge, and technology to ensure implementation.

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2. REVIEW OF LITERATURE

The United Nations Sustainable Development Goals (SDGs) have set a global agenda to tackle critical issues such as poverty, urbanization, climate change, and inclusive development by 2030. Topology, a branch of mathematics focusing on properties of space preserved under continuous deformation, has emerged as a key tool for addressing spatial and connectivity challenges inherent in sustainable urban development. This literature review systematically examines research on the applications of topology in urban planning, informal settlement mapping, and related sustainable development efforts aligned particularly with SDG 11 (Sustainable Cities and Communities).

2.1 Urban Morphology and Topology in Informal Settlement Mapping

Ganchozo Llano (2024) pioneered a methodology combining urban morphology and topological analysis to precisely identify and map slums using open geospatial data sources like OpenStreetMap. This approach addresses significant issues in data scarcity and imprecision common in informal settlement documentation. By calculating topological relationships in building footprints and quantifying spatial parameters, the study offered a replicable and scalable framework tested across Bangladesh, Uganda, and Paraguay. Its relevance to SDG 11 emerges from enabling more effective urban planning and resource allocation strategies that promote inclusive, resilient urban environments.

2.2 Analyzing Neighborhood Connectivity via Topology

Brelsford et al. (2018) contributed substantially by conceptualizing urban neighbourhoods as interlinked networked spaces: the **access network** comprised of streets and pathways and the **place network** of buildings and amenities. Distinguishing between formal and informal settlements based on their topological characteristics, the study revealed that slums exhibit distinct topological deficiencies, particularly in connectivity and spatial access. By applying constrained optimization algorithms, the researchers identified cost-efficient infrastructure modifications capable of transforming slums towards connectivity parity with formal cities. Applied case studies in Cape Town and Mumbai highlighted measurable improvements in quality of life indicators, directly supporting SDG 11.

2.3 Urban Mobility and Network Structure

Herrera-Acevedo et al. (2025) explored how urban network topology influences urban mobility readiness across numerous global cities. The study demonstrated that cities with higher topological connectivity show better accessibility to services and urban resilience, thus linking spatial network properties to broader socio-demographic outcomes. This reinforces topology's critical role in designing sustainable urban transport and infrastructure systems essential for equitable city living.

2.4 Systematic Literature Reviews on Topology and Sustainability

Comprehensive reviews by Faheem et al. (2024) and Karal et al. (2024) emphasize topology's increasing relevance across sustainable development sectors, including circular economy models, industrial innovation, and urban resilience. They highlight the adaptability and robustness of topological tools in optimizing resource use, reducing environmental impact, and supporting smart city initiatives aligned with various SDGs.

2.5 Governance and Practical Challenges in Informal Urban Contexts

Sharifi (2024) and others have shed light on governance challenges involved in applying topological and digital mapping tools to informal settlements. While topology offers powerful analytical capacity, translating findings into effective local policies requires context-sensitive governance frameworks and participatory planning processes. Digital inclusion, data quality, and community engagement are identified as key enablers for success in sustainable urban upgrading using topological approaches.

2.6. Theoretical and Methodological Advances

Recent literature highlights the synergy between Topological Data Analysis (TDA), Geographic Information Systems (GIS), and network theory in capturing spatial complexities of urban environments. These methods can handle noisy or incomplete datasets common in informal areas and uncover latent connectivity patterns essential for sustainable planning. Computational innovations and open-source platforms have broadened accessibility and use cases, enabling multidisciplinary adoption of topological frameworks.

3. TOPOLOGY AND THE UNITED NATIONS SUSTAINABLE DEVELOPMENT GOALS

3.1 Sustainable Cities and Communities (SDG 11)

Urbanization pressures demand efficient city planning and infrastructure that supports inclusivity, resilience, and sustainability. Topological tools enable mapping and enhancing connectivity in both formal and informal settlements**.** The detailed review and study of the work done motivates to introduces following two case studies to understand the complete process of slum mapping using Topology.

Case Study 1: Slum Mapping Using Urban Morphology and Topology

Ganchozo Llano's (2024) master thesis develops a novel approach combining urban morphology and topology to map slums accurately for SDG 11. By analysing open-source geospatial data (OpenStreetMap) and computing topological relationships between building footprints, the method provides a framework for identifying slum boundaries and characteristics in Bangladesh, Uganda, and Paraguay. This enables more precise urban planning, better resource allocation, and community empowerment.

The key contributions of this case study include:

- Development of scalable algorithms for topological analysis in large spatial datasets.
- Quantitative parameters capturing urban density, connectivity, and accessibility.
- Focus on participatory approaches integrating local knowledge with digital mapping.

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This research significantly advances capabilities for informal settlement planning, a critical step toward resilient and inclusive urbanization. As shown in figure 2, connectedness of topological spaces contributes to SDG 11 goals in public services, road networks, improvement of infrastructure, community inclusion, etc.

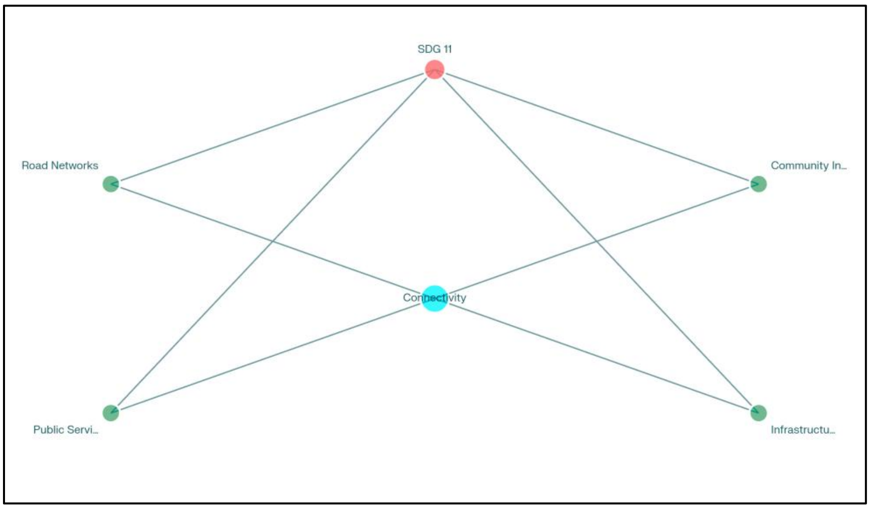

Figure 2: Connectedness and SDG 11

Case Study 2: Theory of Spatial Evolution of Urban Neighbourhoods

Brelsford et al. (2018) formalized the urban environment as dual networks: the access network (streets, roads) and the place network (buildings, public spaces). The topology of these networks was analysed to reveal inherent patterns in formal and informal neighbourhoods globally. Their work produced algorithms to:

- Detect deficits in connectivity and spatial accessibility.
- Propose new, minimum-cost street additions to improve slum neighbourhoods' access.
- Quantify improvements in social mixing, infrastructure equity, and service delivery.

Applied in Cape Town and Mumbai, these insights assisted planners to integrate informal areas into formal city frameworks, advancing SDG 11 targets of safe and inclusive cities.

3.2.Affordable and Clean Energy (SDG 7)

Topology guides the optimization of energy grids, improving efficiency by minimizing energy losses and facilitating renewable integration. Topological design in district heating/cooling networks reduces operational costs and environmental impact.

3.3 Climate Action (SDG 13)

Topological models help understand resilience boundaries in environmental systems. By identifying "safe operating spaces," these tools aid policymakers in designing interventions to keep climate systems within tolerable states. Topological approaches also contribute to understanding ecological networks and their resilience under climate stress, which is critical for informed policy and ecosystem management related to SDG 13 targets, as shown in figure 3. Assisting in the design of early-warning systems for climate tipping points based on changes in the topology of climate attractors.

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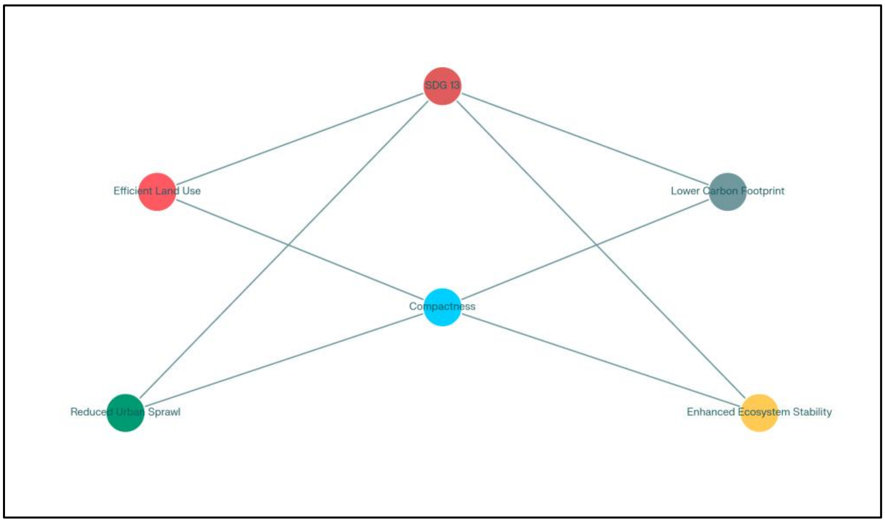

Figure 3: Compactness and SDG 13

3.4 Good Health and Well-being (SDG 3)

Topology, particularly through methods like Topological Data Analysis (TDA), is increasingly applied in medicine and biomedical research. Here are notable applications:

- Medical Imaging Analysis: TDA provides powerful tools for analysing the complex, high-dimensional data produced by medical imaging modalities such as CT, MRI, and ultrasound. It can identify patterns and global structures (like loops and voids) in image data that are not easily captured by traditional metrics, helping to differentiate between tissue types, track disease progression, or segment tumors. TDA is used in tumor characterization, treatment response prediction, and to aid in diagnostic support for diseases such as lung cancer, traumatic brain injury, pulmonary embolism, and diabetic retinopathy.
- Tumor Characterization and Oncology: Persistent homology—a core tool in TDA—has been applied to predict survival rates, segment tumors, classify disease states, and identify biomarkers from images and genomic data. For example, topological signatures can differentiate tumor subtypes and even predict patient stratification and prognosis for cancers such as gliomas and lung adenocarcinoma.
- Organ Identification and therapeutic planning: Topological numbers (such as Euler characteristics in 3D digital topology) assist in identifying organs and planning treatment, by quantifying shape and structural properties critical for organ identification and segmentation.
- In biomedicine, as shown in figure 4, topology and specifically knot theory helps decode protein folding, DNA structure, and brain connectivity. These insights underpin precision medicine, drug discovery, and diagnostics, aligning healthcare advancements with SDG 3 goals.

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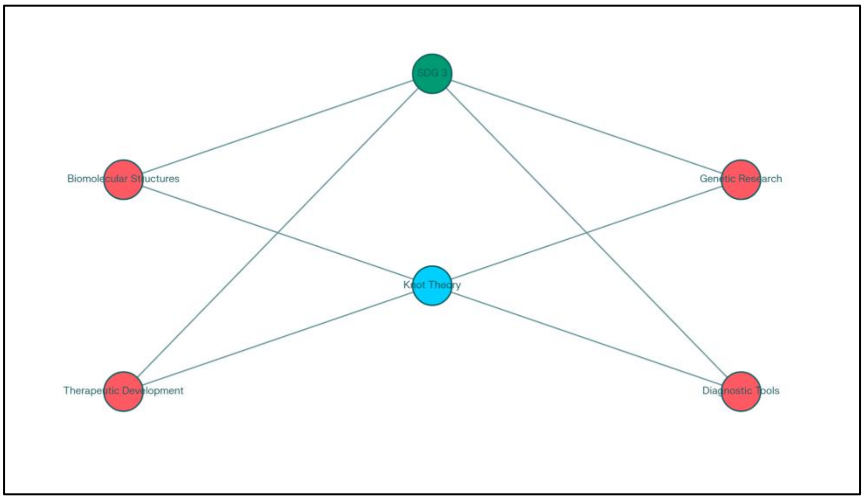

Figure 4: Knot theory and SDG 3

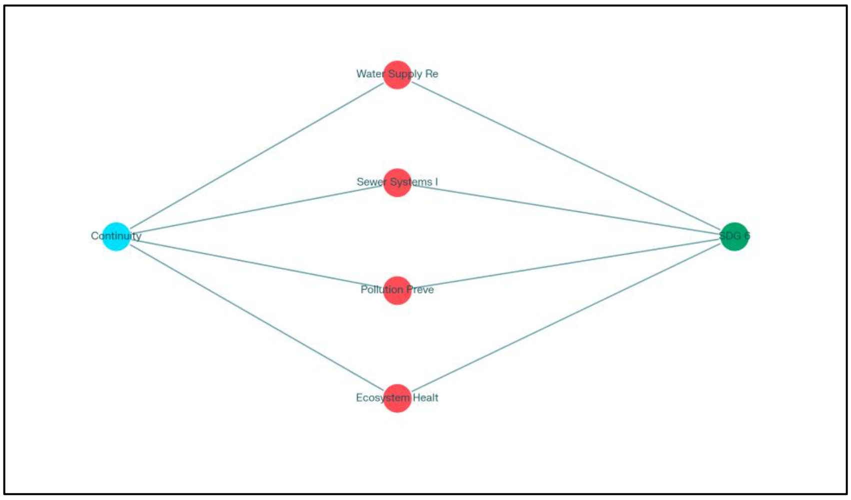

Figure 5: Continuity and SDG 6

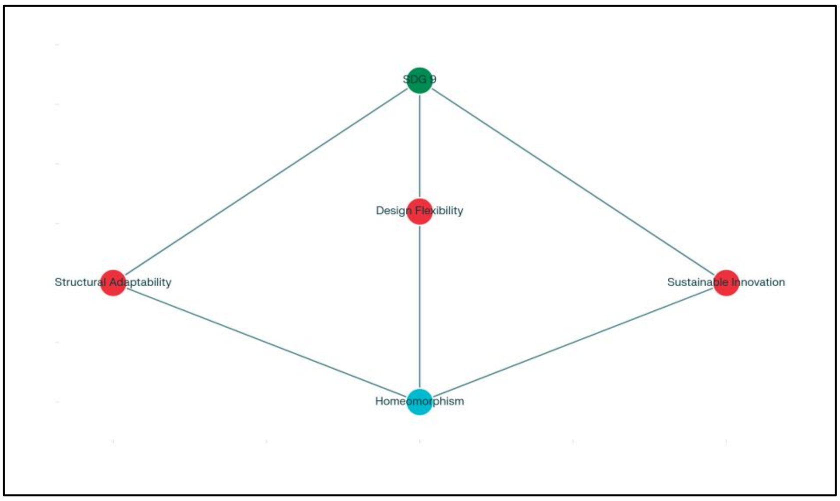

Figure 6: Homeomorphism and SDG 9

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4. METHODOLOGY AND TOOLS

4.1 Topological Data Analysis (TDA)

TDA extracts meaningful shape information from high-dimensional data. Using persistence diagrams and homology, it identifies features invariant under continuous transformations—key for noisy or incomplete data in urban, environmental, and biomedical contexts.

4.2 Geographic Information Systems (GIS) and Open Data

Urban planners utilize GIS tools integrated with open data OSM (OpenStreetMap) to map connectivity, building footprints, and spatial organization. Topological algorithms applied on this data uncover hidden structural patterns critical for planning.

4.3 Network Theory and Optimization

Using graph theory, urban spaces and infrastructure are modeled as nodes and edges. Optimization techniques identify minimal additions or modifications to enhance connectivity, flow, and resilience.

5. RESULTS AND DISCUSSION

5.1 Topology linked to SDGs

The theory of continuity, homeomorphism, compactness, connectedness and knot theory is linked to the particular relevant SDGs as shown in figures 1, 2, 3, 4 and 5, in order to find solutions and to achieve specific sustainable development goal. This shows an emerging application of Topology in real world and also encouraging to achieve 2030 Sustainable Development agenda.

5.2 Enhanced Slum Mapping and Urban Planning

The integration of topological metrics improves the granularity and accuracy of slum maps. These maps better reflect real-world informal settlement boundaries and building connectivity, enabling targeted infrastructural upgrades and social programs.

5.3 Cost-effective Infrastructure Upgrades

The spatial evolution approach demonstrates that minimal street additions significantly improve access to services in slums, reducing isolation and socioeconomic disparities. These interventions are low-cost yet impactful, making urban upgrading feasible for low-resource cities.

5.4 Broader Societal Impacts

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By applying topological principles and applications, cities can become more equitable and resilient, energy systems more efficient, and health systems more precise, all advancing the 2030 Sustainable Development agenda.

5.5 Advantages of Topological Approaches

- Robustness: Topological methods mostly focus on the qualitative properties of spaces and structures that remain invariant under continuous deformation such as stretching or bending. This makes them inherently less sensitive to noise, distortions, or small measurement errors that often affect spatial or network data. For example, unlike purely geometric methods that rely on exact distances or angles, topology abstracts away these metric details, providing stable insights even when data is incomplete or imperfect. This robustness is particularly valuable in environmental modeling, urban mapping, and biomedical applications where datasets often have uncertainties.

- Scalability: Topology's abstract nature allows it to be applied across vastly different scales—from microscopic biological structures such as protein folding and neural networks, to large-scale systems like urban infrastructure and global climate models. This scalability facilitates interdisciplinary research and enables holistic sustainable development strategies that connect micro-level phenomena (e.g., molecular biology) with macro-scale challenges (e.g., city planning).

- Interdisciplinary: Topological frameworks bridge multiple domains—pure mathematics, geography, computer science, urban planning, environmental science, and social science. This cross-disciplinarity fosters innovative solutions that combine theoretical rigor with practical implementation. For instance, combining topological data analysis with geospatial information systems helps analyse complex urban morphology and improves planning for the Sustainable Development Goals.

5.6 Challenges and Limitations

- Data Quality: Reliance on accurate spatial data can be limiting.
- Computational Complexity: Large datasets require sophisticated algorithmic solutions.
- Integration into Policy: Translating mathematical results into actionable policy remains a hurdle.
- Theoretical concepts: Implementing theories to the problem in order to solve it or link it with, can be difficult for initial stage.

5.7 Future Directions

Topology and Machine Learning can be combined and that can achieve many SDGs, specifically for predictive urban analytics. For example, topological features can be used as inputs to train models that forecast urban growth, traffic patterns, or social vulnerabilities, enhancing proactive planning and disaster response aligned with SDG objectives.

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Implementing real-time topological monitoring can revolutionize climate adaptation and energy management. For instance, continuous analysis of spatial and network data from sensor arrays can detect emerging instabilities or inefficiencies, enabling timely interventions for climate resilience (SDG 13) and sustainable energy provision (SDG 7).

Future tools incorporating topology should emphasize participatory approaches, allowing local communities to contribute spatial knowledge and collaborate in mapping informal settlements or infrastructure needs. This democratizes data generation, improves accuracy, and ensures that solutions reflect lived realities, empowering marginalized populations consistent with the SDG ethos.

6. CONCLUSION AND RECOMMENDATIONS

A theoretical subject like Topology can have applications in real world and specifically provides a versatile, powerful framework for understanding and managing spatial and networked challenges fundamental to sustainable development. From mapping concepts of Topology to the UN SDGs by fostering inclusive, resilient, and adaptive environments. This also strengthens collaboration between mathematicians, urban planners, policymakers, and communities, and there we unlock topology's full potential as a driver of sustainable futures.

It is recommended that future research explicitly integrate mathematical principles with sustainability goals to maximize global impact, and this application also emerge the young minds to study the subject Topology.

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