Using Agent Based Simulation to Model Informal Growth of Infrastructure

Hossein Vahidi
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by

Hossein Vahidi

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Thesis Assessment Board

Chair:	Dr. R.A. de By
External examiner:	Ms. B. Pérez Lapeña, MSc.
Supervisor:	Ms. Ir. P.W.M. Augustijn
Second supervisor:	Dr. R. Zurita-Milla

FACULTY OF GEO-INFORMATION SCIENCE AND EARTH OBSERVATION OF THE UNIVERSITY OF TWENTE
ENSCHEDE, THE NETHERLANDS

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Abstract

Informal settlements are rapidly developing regions which are suffering severely from the lack of legal supervision. Informal settlement growth is a complex phenomenon causes by different dynamics. These dynamics influence each other, which increases the complexity of the system. The construction of buildings in these settlements (housing) and the growth of infrastructure are two main components of the informal development of the settlement which influence each other over time. Some studies have been done to understand the mechanism of informal growth of settlement, but not enough attention has been paid to study the informal growth of infrastructure dynamic.
This research aims to extend an already existing (agent-based) housing model with a vector based model for microscopic simulation of infrastructure growth, using an agent based technique with a case study for an informal settlement in Dar es Salaam, Tanzania. The driving forces and characteristics of the informal infrastructure growth are studied to understand the complex patterns which emerged in the context of informal infrastructure. Analyses are grouped into three categories: the relationship between infrastructure and environment, the geometric relationships in infrastructure and the relationship between buildings and infrastructure. Existing infrastructure was classified into four types of infrastructure (formal, collectors, local trails and personal trails) and analyses were done for each infrastructure type. The results of these analyses show that different types of infrastructure show different characteristics. Based on these findings, two different mechanisms of infrastructure growth were identified. The first mechanism which plays the main role in the formation of infrastructure inside the informal settlement is based on the needs of the residents for providing accessibility to the higher ranks of infrastructure. The second mechanism develops the infrastructure based on the needs of the residents to reach different destinations to perform their daily activities. A conceptual model was developed that includes these two mechanisms. To evaluate the possibilities of implementing this conceptual model some prototype tests were conducted.

Keywords: Agent based modelling, Informal settlement, Infrastructure growth, Trail formation, Infrastructure pattern.

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1. Introduction

1.1. Motivation and problem statement

Informal settlements are rapidly unplanned developing regions which are suffering severely from the lack of legal supervision. Development of these areas (besides changing the urban structure) leads to increase of poverty, inequality and social exclusion in the major cities of developing countries (Sietchiping, 2005). Increased knowledge about the factors that influence the growth of these settlements, and their effect mechanism, may help responsible authorities to manage and plan for facilities (such as health care, water supplying systems, pipelines and electrical transmission lines) and prepare the effective social, economical and physical plans to directly or indirectly control the direction of urban growth.

Dynamic urban systems like informal settlements include two main components: buildings and infrastructure (roads and footpaths). As the urban system has a complex dynamic nature these components influence each other over time. According to Sliuzas (1988) study, informal settlement occurs mainly along infrastructures. The infrastructure growth influences the pattern of building growth in the study area and it can cause the construction of new buildings around expanded infrastructure. Also it could be expected that the new buildings can cause the generation of new travels in the study area which can lead to a new phase of infrastructure growth. Infrastructure undertakes the role of connection between significant destinations and also provides the accessibility of zones and facilities for human and vehicle in the area.

Informal growth of infrastructure has a bottom up nature. This process starts when a track is created by a single settler. This track will develop into a footpath when it is used frequently by many people. If and when a footpath will develop is based on the different behavior of settlers and is influenced by various social, economical and physical factors such as age and gender of settlers, the security situation of the location, the economical casts of the residents, topography and physical obstacles. Besides the bottom up development, it is observed that there are some top down governmental interference in the dynamic of informal infrastructure growths phenomenon. These are mostly related to the upgrading of unpaved footpaths to formal paved roads.

Simulation models can help to investigate the factors that influence infrastructural growth and gain a better understanding of the dynamics between settlement growth and the development of infrastructure but also the factors that influences the locations where infrastructure will grow. Yamins et al. (2003) studies indicate that little attention have been paid to modeling of transportation infrastructure growth by researchers in comparison to settlement (building) growth modeling. Several types of infrastructure growth models exist. Huang & Levinson (2009) divide infrastructure growth models in to three main categories: probabilistic network growths models, network design models and agent based models.

Majority of the models in the first and second category, have a top down nature and do not consider various physical, economical and social factors as the growth driving forces. Also most of these models are at the macro scale levels which do not provide the ability of study of the growth dynamic at the micro scale level.

Agent based simulation models are bottom up, individual based and are therefore suitable to simulate the growth of infrastructure as a result of settlers behavior. This modeling approach allows for

modeling heterogeneity of agents (different settlers) and different behavior of them in the interaction with each other and also with the environment.
Previous agent based simulation models for infrastructure growth mostly concentrated on the modeling of formally planned and structured settlements. They cannot handle the simulation of the informal growth of infrastructure which have complex irregular pattern. Previous researches are also primarily cellular based simulations which do not include geometry in the modeling process.

1.2. Research objectives

The main objective of this research is to develop a vector based model for microscopic simulation of infrastructure growth, using an agent based technique with a case study for an informal settlement in Dar es Salaam, Tanzania. The sub objectives of this research are as follows:

- To identify and analyze driving forces which influence the informal growth of infrastructure of informal settlement in Dar es Salaam.
- To identify the different dynamics in the formation of informal infrastructure.
- To develop a conceptual model for the simulation of infrastructure growth in Dar es Salaam.
- To implement the conceptual model as a prototype.
- To evaluate the contribution of the driving forces to the growth process.

1.3. Research questions

This research addresses the following questions:

- What are the existing infrastructure growth models and how do they model the social, economical and physical factors?
- How to analyze the driving forces that influence the growth of infrastructure?
- What are the different dynamics in informal growth of infrastructure?
- What are the agent's characteristics and behaviors?
- Which environments need to be implemented and which interactions between agents and environments?
- How can the dynamics between infrastructure and houses be simulated?

1.4. Method adopted

In order to achieve the research objectives and answer to the research question, the research will follow a methodology. The adopted methodology for the research includes:

- Reviewing the past studies and relevant literatures to understand the existing models on infrastructure growth.
- Defining the list of possible driving forces that influence the growth in infrastructure of informal settlement in Dar es Salaam.
- Analyzing the possible driving forces driving forces which influence the growth of infrastructure of informal settlement in the three categories of: The relationship between infrastructure and environment, geometric relationships in infrastructure and the relationship between buildings and infrastructure.
- Defining the behaviors and characteristics of agents and environment.
- Defining the rules of modeling to model the interactions between agents and agents, between agents and environment and between the components of the environment.
- Designing of the conceptual model for different mechanisms of informal infrastructure growth based on what were defined in previous steps.
- Implementation of the prototype model.

- Evaluation of the prototype model's results and conclusion and recommendation for future works.

1.5. The outline of the thesis

This thesis is organized in six chapters. Chapter one introduces the context of the research, including the research problems and describes the research objectives and question and research methodology.
Chapter two reviews the concept of informal settlement and introduces the characteristics of informal settlement in Dar es Salaam as the study area of this research. The chapter describes the different simulation approaches and reviews the existed infrastructure growth models. Also the other concepts which will be used in the next chapters will be introduced in the chapter two. Chapter three focuses on the analysis of informal infrastructure growth driving forces and characteristics. This will be studied in three headlines of: the relationship between infrastructure and environment, geometric relationships in infrastructure and the relationship between buildings and infrastructure. In the chapter four, an agent based model with two components will be introduced for the informal growth of the infrastructure. The first proposed component focuses on the informal infrastructure growth process which provides the initial houses accessibility in the informal settlement. The second proposed component describes the informal infrastructure growth model for formation of the trails to/between the centers.
In the chapter five the results of the prototype model which is implemented based on the concepts of the first proposed model for informal infrastructure growth in the chapter four will be evaluated. Finally, chapter six concludes the research content and discusses the limitations of this study and proposes some recommendations and possible studies for future.

2. Background and Theories

2.1. Introduction

The first part of this chapter describes the concept of informal settlement and introduces the characteristics of the informal settlement in Dar es Salaam. The chapter will describe the different simulation approaches and it will review the concepts of agent based modelling in the second part of this chapter. The existed infrastructure growth models will be reviewed and discussed in third part of this chapter. The last part of this chapter will review the concepts of infrastructure hierarchy classification systems, measurement of the complexity, synthetic population and activity based travel modelling which will be used in the next chapters.

2.2. Informal settlement

Rapid informal growth of settlement is a common phenomenon in many developing regions in all parts of the world. UN-Habitat (2003) study shows that 924 million people around the world (31.6 per cent of the world's urban population) live in informal settlements. This study shows that 71.9 per cent of urban population of the sub- Saharan region settled in informal settlements in 2001 which was the greatest proportion of the informal settlement within the developing regions of the world.

There is no single definition on the concept of informal settlement as this can be defined based on the different aspects of the informal settlement and various social, economical and environmental parameters. For example, UN-Habitat (2003) defines informal settlement (slum) as: "a contiguous settlement where the inhabitants are characterized as having inadequate housing and basic services. A slum is often not recognized and addressed by the public authorities as an integral or equal part of the city". UNCHS (1999) describes the informal settlement (slum) as "neglected parts of cities where housing and living conditions are appallingly poor. Slums range from high density, squalid central city tenements to spontaneous squatter settlements without legal recognition or rights, sprawling at the edge of cities."

The constructions in the informal settlement are often unlike the legal laws and regulations and suffer from the lack of formal planning (Sietchiping, 2005). UN-Habitat (2003) indicates that many of the informal settlements are overcrowded and they have high population density (space per person) which reduces the quality of life in these areas.

Poverty is one of the common characteristics of informal settlements. Informal settlement usually takes place in the vacant cheap or valueless lands like abandoned lands, flood prone areas, steep slopes or dumping grounds which where the low income groups can build their houses with the low quality and cheap materials.

Lack of adequate basic public services is one the main problem of informal settlements. Lack of access to safe water, sewerage systems and health care system are the examples of the shortage of the basic public services which reduce the quality of living in the informal settlement.

Infrastructure under development is one of the main problems in the informal settlements. The informal infrastructure has an unplanned and unstructured organic growth. The informal infrastructure network is often not expanded well in the settlements and they suffer from the unsuitable surface condition and lack of governmental maintenance.

2.2.1. Informal settlement in Dar es Salaam

Dar es Salaam is the largest city of Tanzania and the most important economic center of the country. The very rapid growth of population and informal settlement in Dar es Salaam is very well-known in the sub-Saharan region which makes great challenges for the government in Tanzania (Table 2.1 & Table 2.2).

Dar es Salaam Populating Size			
1969	**1978**	**1988**	**2002**
356,285	843,090	1,360,850	2,497,940

Table 2.1: Population growth of Dar es salaam 1969-2002 (Tanzania bureau for statistics)

Population Growth Rate		
1969-1978	**1978-1988**	**1988-1992**
7.8%	4.8%	4.0%

Table 2.2: Population growth rate of Dar es salaam 1969-1992 (Tanzania bureau for statistics)

Ramadhani (2007) shows that Dar es salaam has the largest number of informal settlement in Tanzania. The number of informal settlement regions in Dar Salaam was 25 regions in 1978, 40 regions in 1985, 50 regions in 2002 according this study (Figure 2.1).

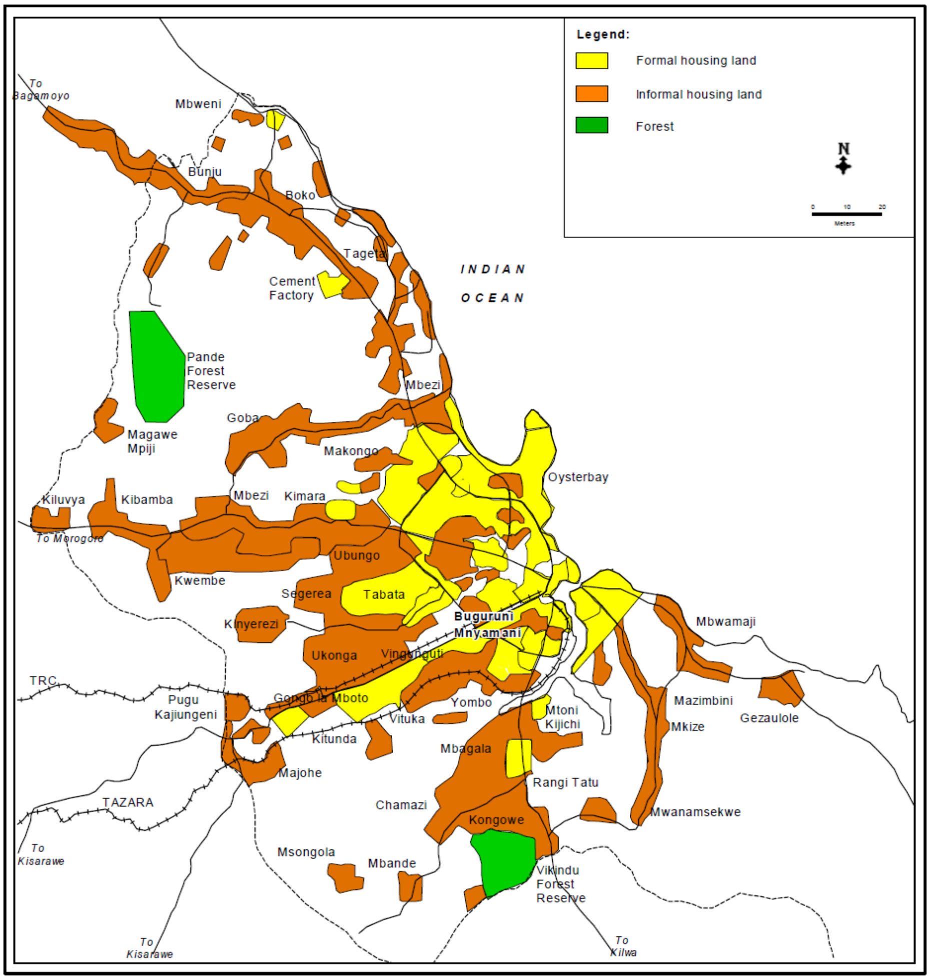


Figure 2.1: Formal and informal settlement in Dar es Salaam in 2002 (Kyessi & Kyessi, 2007)

The Lupala (2002) study indicates that approximately 127500 house units from the 170000 house units in Dar es Salaam (75% the house units in the city) were located in the informal settlement regions.
As the main portion of the settlement has grown informally in Dar es Salaam, the infrastructure has been developed informally in the slums in order to provide the accessibility of the residents in to their destinations. Kanyama et al. (2004) shows that the main portion of infrastructure in Dar es Salaam has been developed informally. A result of a study by the Tanzania government in 1992 showed that only 2.3% of roads were developed under the investment and provision of the government (Kanyama, et al., 2004).
The government has been trying to increase the construction of formal infrastructure in the recent decade in Dar es Salaam. They also try to remediate and upgrade the existed informal infrastructure in Dar es Salaam by formalisation programs.

2.3. Modeling and simulation

Modeling is the simplified representation of the real world. It is the process of generating a model to understand a complex system or phenomenon and test a theory.
In the context of urban modelling, different modeling techniques exist and used. Before 1960s, the urban models had a static characteristic and they did not strengthen enough to model the dynamic nature of the urban growths proper and practical way (Liu, 2009). By the development of digital computing after 1960s, the different techniques of urban modeling are developed to model the urban issues in the fields of the land use, transportation, population and urban economical activities with respecting to to their dynamic nature (Liu, 2009).
As the geographical information system (GIS) have been developed in the recent decades, the urban models have been integrated with GIS technology to benefit from a rich data source, the functionalities of this system and the analytical capabilities of it (Liu, 2009). As Liu (2009)indicates, these advances in the field of modeling cause to open new horizons in the field of urban modeling.
The modeling techniques of cellular automata and agent based modeling have been widely used recently in the field of urban dynamics simulation (Batty, 2005). The following sections will focus on these techniques and review the concepts of these modeling methods.

2.3.1. Cellular Automata technique

Wolfram (1994) defines a cellular automata (CA) as a discrete system in which the space is in divided to the uniform and regular lattice of cells. In each discrete time step, each cell in the lattice can have only one state from the finite set of cell states. The cell state is changed in each time step based on the previous state of the cell and its neighbor.
A cellular automata system consists of five basic components of the cell, state, neighborhood and transition rule *(Liu,* 2009*)*.
Liu (2009) describes the cell as “basic spatial unit in a cellular space”. A two dimensional cells lattice is the most popular arrangement of cells. However the other arrangement of tessellation like one or three dimensional arrangement with the different forms like honeycomb can be seen in the literature.
The state of the cell represents the attributes of the system.
The neighborhood a cell are the adjacent cells which they have an interaction with a cell and the state of them have an influence on it. The neighborhood of a cell can be defined in the different forms like: von Neumann neighborhood (four cells), Moore neighborhood (eight cells), Moore von Neumann, H neighborhood and circular neighborhood (Batty, 2005).
The transition rule as the key component of cellular automata defines the state of each cell in each time step according to the previous state of the cell and its neighborhood (O'Sullivan & Torrens, 2000).

The time as the last component of cellular automata defines the temporal dimension in which a cellular automaton system progress in it. The time progresses in the desecrate iterations (Wolfram, 1994).
The bottom up nature of cellular automata provide a considerable platform for modeling of urban dynamic based on the idea that a complex global patterns originate from the local rules(Barros, 2004).
One of the strengths of this approach is the simplicity of the model construction.
The model can be built based on some simple local rules, however they can generate very complex patterns as the system progress in the time based on the self organization and self reproduction characteristics of this approach (Liu, 2009).
As cellular automata approach has a cell based structure, it can be easily integrated with GIS technology because of this approach is compatible with raster GIS (Liu, 2009).
However there are some weaknesses which limit the application of cellular automata approach for modeling of urban dynamics.
The cellular automata approach has a limitation to hold the geometric and the topologic details of the urban system with non regular grid form as it is based on the cellular environment (Batty & Torrens, 2001).
One of the other limitation of cellular automata technique is the distance decay effect is not considered in the concept of the neighborhood which it is unlike the reality in urban systems (Liu, 2009)

2.3.2. Agent based modelling

Many researchers diverted their attention from the previous simulation techniques to the new paradigm of agent based modeling (ABM) in the last decades because of the limitations of the previous modeling techniques.
An agent based model is a type of computational models for simulation of the behaviors of autonomous individuals or collective entities with the bottom up approach. It includes of four main components of agents as autonomous decision making entities, an environment where the agents interact in that, rules that determine the relationship between agents and the environment, and rules that define sequencing of actions in the proposed model (Parker, Berger, & Manson, 2001). There is no single definition on the term of “agent” in the literatures.
Macal & North (2005) divides these different definitions on the concept of agent into two main categories. Some researchers define any type of independent component as an agent. The agent in this category of definition can have a primitive behavior, like a reactive decision rules or a complex behavior, like an adaptive intelligence. Other researchers emphasize that an agent must have an adaptive behavior which means that the agent has learning ability and it can change its behavior based on the previous experiences in the environment.
Franklin & Graesser (1997) introduced the main properties of an agent(Table 2.3). This range of properties includes the properties of the agent with a primitive behavior and the agent with an adaptive behavior.

Property	Meaning
Reactive	Responds in a timely fashion to changes in the environment
Autonomous	Exercises control over its own actions
Goal-oriented/Proactive/Purposeful	Does not simply act in response to the environment
Temporally continuous	Is a continuously running process
Communicative/Socially aware	Communicates with other agents, perhaps including people
Learning/Adaptive	Changes its behavior based on its previous experience
Mobile	Able to transport itself from one machine to another
Flexible	Actions are not scripted
Character	Believable personality and emotional state

Table 2.3: Properties of an agent (Franklin & Graesser, 1997)

Agent based simulation provides a powerful platform for the modeling of the complexity in the real world and enables the modelers to test their hypotheses about the rules which cause to a complex behaviors of a system in the real world. Agent based models were vastly applied in many areas of science. These application fields are varying widely which the sociology, economics, ecology, anthropology, cognitive science and earth sciences are a few examples of them.

The agent based modeling paradigm cause to change the previous static, aggregate and centralized simulation techniques to the dynamic, disaggregate and decentralized approaches. These characteristics and advantages of the agent based modeling technique caused to widespread use of this technique in the simulation of the urban dynamics.

By the application of the agent based modeling approach, the complex and aggregated behaviors of the city can be understood. Also the complex patterns in the dynamics of the city can be study based on the different actions and decisions of the individuals who act and react in the urban context. This dynamic approach can provide a powerful platform for the mangers and urban planners to study the influences of their decisions on the city dynamics in the microscopic and macroscopic levels .It also help them to provide the strategies and plans for the future based on the results of the simulation of the urban growth.

2.4. Infrastructure growth simulation models

Some studies have been done to simulate the growth of infrastructure in urban areas. Huang & Levinson (2009) studied these researches and divided these models in to three main categories: probabilistic network growths models, network design models and agent based models.

Researchers like Frank & Strauss (1986), Dorogovtsev & Mendes (2002) and Gastner & Newman (2006) proposed probabilistic network growth models based on the idea that each road (link) is presumably generated with a probability.

In the second category, the researchers like Schweitzer et al. (1996), Yamins et al. (2003) and Barthelemy & Flammini (2008) focused on the network design models. This approach claims that a road (link) is built to optimize a centralized objective such as minimizing the Euclidean distance or the travel time or maximizing transportation potential between two zones (A. Huang & Levinson, 2009).

The agent based simulation as a third approach has become more popular in urban modeling since the late 1980s when the computing power of computers and efficiency of the data storage have been improved (Iacono, Levinson, & El-Geneidy, 2008).
Few researches have been done in the field of agent based simulation for infrastructure growth. For example, Helbing et al.(1997) proposed a model for the simulation of ant and human trail formation based on an active walker model. Yerra & Levinson (2005) simulated the formal network growth by the usage of localized investment rules. Also Levinson & Yerra (2006) developed a model to simulate the formal growth of transportation network elements which has a travel demand, revenue, cost and investment as its components. Huang & Levinson (2009) designed a model which was based on the assumption that self interested land parcel owners built formal roads to increase the accessibility in order to the parcel value will increase.
In the following sections, Barthelemy & Flammini model (2008), Huang & Levinson model (2009) and Helbing et al.'s active walker model (1997) will be reviewed as the examples of infrastructure growth simulation models.

2.4.1. Barthelemy & Flammini Model

Barthelemy & Flammini (2008) were proposed a model for simulation of urban streets. Their model is in the line of network design approaches. The proposed model is based on the local optimization principle and inspired from the previous studies on the leaf pattern formation.
The proposed model generates the new vertices (representing new economical centers, etc.) at every T_c (T_c>1) time steps and they are distributed randomly in the study area.
The network of roads that is grown by this model is based on the local optimization principle to connect new vertices to the network with the minimum possible road length. For this purpose the road segments (with the fixed length) are formed at every T_r (T_r =1< T_c) time steps and are added to the existed network.
Barthelemy & Flammini described their model for the simple case where the two vertices of A and B need to be connected to the existed network (this model can be developed for the situation where more than two vertices need to connect to the network).
M_1 and M_2 are the closest points in the network to the unconnected vertices of A and B respectively. Two different scenarios can be happened: ($M_1 \neq M_2$) or ($M_1 = M_2 = M$).
In the first case that $M_1 \neq M_2$, the two independent road segments are generated along the lines M_1A and M_2B.
In the second case that $M_1 = M_2 = M$, in order to minimize the cumulative distance from the vertex M to the unconnected vertices of A and B, the following approach is used by this model (Figure 2.2).

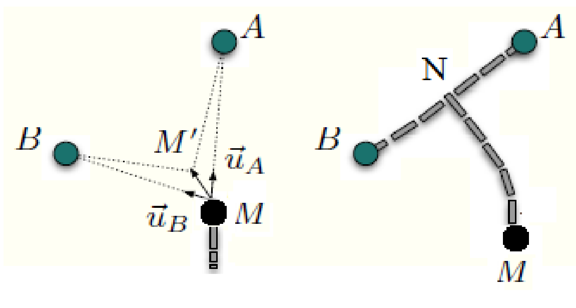


Figure 2.2: Formation of road in the case that M is the closest point to both point A and B (Barthelemy & Flammini, 2008)

If Δ is maximized the reduction of cumulative distance from M to A and B will be maximized. Where:
$\Delta = [d\,(M, A) + d\,(M, B)] - [d\,(M', A) + d\,(M', B)]$
By the consideration of |MM′| =const.≪ 1 as the constraint, the calculation leads to:
$\overrightarrow{MM'} \propto \overrightarrow{uA} + \overrightarrow{uB}$
where $\overrightarrow{uA}$ and $\overrightarrow{uB}$ are the unit vector from the M to A and B.
The road is generated in direction of $\overrightarrow{uA}$ and $\overrightarrow{uB}$ in each time step until the singularity condition occurs with $\overrightarrow{uA} + \overrightarrow{uB} \approx 0$ at the intersection point N (figure 1). In this condition, two independent road segments are generated from the intersection point to A and B.
This model is proposed for the simulation of formal streets (which are developed by the development plans under the supervision of the government) in the urban areas. It focuses on the simulation of top down process of urban infrastructure growth by the government. So, the proposed approach for the minimization of the cumulative distance of unconnected points to the network is based on the economical logic of government and related sectors to minimize the formal road construction costs. The optimization logic of pedestrians which form the paths in the bottom up approach is different from the proposed approach. The pedestrians try to make a compromise between the parameters of direct path (shortest path) construction between the unconnected points and the closest existed point in the network and the parameter of using of common existed paths in the network.
Barthelemy & Flammini model does not consider the different social and economical driving forces which can influence the road formation process.
Also, the proposed model does not consider the environmental factors and existed physical obstacle in the study area.

2.4.2. Huang & Levinson Model

Huang & Levinson (2009) used an agent based microscopic approach to model the road growth in the urban areas. They assumed that the new roads are formed by the self-interested land owners to increase the accessibility of their land parcels and consequently, the value of their land parcels (A. Huang & Levinson, 2009). In this model, the city center was assumed to be pre-existed with the highest economic value of accessibility in Huang & Levinson's study (A. Huang & Levinson, 2009). The model which was proposed by Huang & Levinson consists of a K×K grid which contains N nodes. These nodes are the representative of N land parcels which have N land owners (A. Huang & Levinson, 2009). In the Huang & Levinson model it was assumed that the roads can only be built parallel to the x or y axis with no over passes (A. Huang & Levinson, 2009).
The road formation is an irreversible process in Huang & Levinson's model and when a road is formed, it will not possible to be disconnected from the network (A. Huang & Levinson, 2009).
The road formation will be continues in Huang & Levinson's model until a stable situation appears and no new road are built (A. Huang & Levinson, 2009).
Participation of parcel owners in road construction is randomly decided (A. Huang & Levinson, 2009). Each parcel owner has two choices in each iteration. The first choice of the owner is to build a new link (or links) between two unconnected land parcels. The second choice of the owner is not build a new link (A. Huang & Levinson, 2009).
Huang & Levinson (2009) defined the maximum benefit function as $P_m(k,t)$ which shows the maximum benefit that can be get in the formation of a link (road) k from the parcel m to parcel j in the iteration t. The maximum benefit function is calculated from the subtraction of its two components.

The gravity function is the first component of the maximum benefit function. The gravity function has a direct relation to value (advantage) of connecting the parcel m to parcel j and has an indirect relation to the shortest path between parcel m and parcel j. The second component of the maximum benefit function is the function which calculates the total cost of road formation which was spent by the land owner m in all iterations (A. Huang & Levinson, 2009).

When the maximum benefit function value in each iteration is bigger than the previous iteration the link k will be build by the parcel owner m (A. Huang & Levinson, 2009).

Huang & Levinson's model is proposed for formal cities with regular structure. And the road formation is limited to the direct links in the grid of parcels which are parallel to x or y axis.

This model can only simulate the parcel owners which want to obtain the maximum economical benefit from the connection of their lands to other parcels.

The other limitation of this model is that the different social and physical driving factors in the process of road formation were not considered in Huang & Levinson's model.

As the Huang & Levinson's model was proposed for formal roads, they assumed that the road formation is an irreversible process and the roads will not be changed after they were built.

So, these limitations will cause the Huang & Levinson's model is not able to simulate the human trail formation.

2.4.3. Active walker model

In order to explain Helbing et al.'s active walker model, it is necessary that some of the basic concepts which were used in this model will be described. In section 2.4.3.1, first the concept of minimum Steiner tree will be described. Helbing et al.'s model will be explained in section 2.4.3.2 as the infrastructure growth simulation model which was developed based on the active walker model. Goldstone et al. (2006) experimented the group path formation process in the software platform. The results of their experiments can describe some of Helbing et al. model results. In the section 2.4.3.3 the results of Goldstone et al. will be reviewed and discussed.

2.4.3.1. Minimum Steiner tree

The problem of finding the shortest total length network (graph) which connect the points (nodes) in the network has a long history in the field of mathematics that date back to the 17^{th} century (Gander, Santugini, & Steiner, 2008). The minimum Steiner tree (MST) concept was proposed in mathematics to formulate a method for connecting a set of points with the shortest total lengths of the network.

The minimum Steiner tree concept is similar to a minimum spanning tree problem. The minimum spanning tree connects all the nodes in the network with direct connections with the shortest total length of the network. The difference between these two concepts is that there is a possibility to add extra new points named Steiner points in a Steiner tree to reduce the total length of network in comparison with the total network length of minimum spanning tree(Goldstone, et al., 2006), (Gander, et al., 2008).Any Steiner tree has the following characteristics (Gander, et al., 2008):

1. Any Steiner point in a Steiner tree connects to exactly three edges and these three edges are separated by three 120 degree angles.
2. Three edges which are connected to a Steiner point create three 120 degree angles.

Figure 2.3 shows the minimum Steiner tree for the configuration of three and four points.

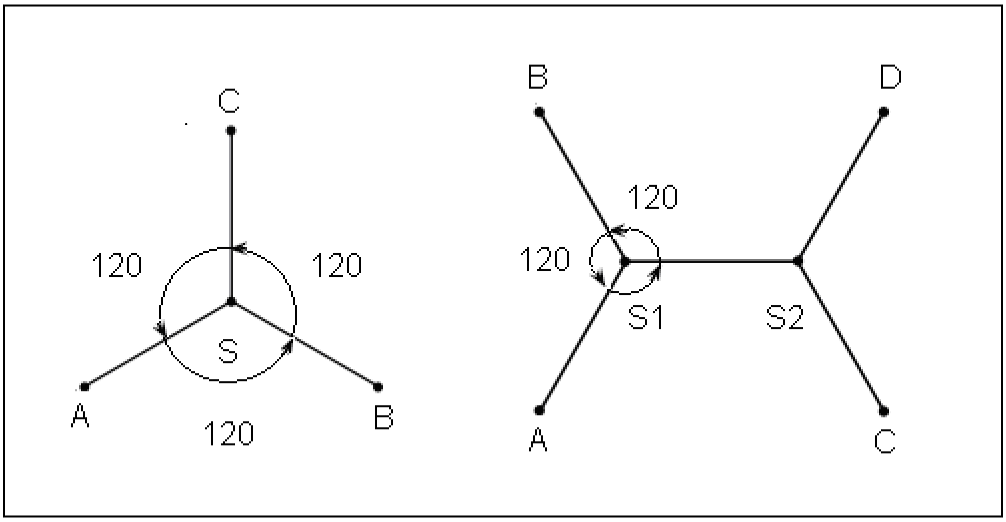


Figure 2.3: Minimum Steiner tree for the configuration of three and four points. Points S, S1 and S2 are Steiner points

It was proven, that as the number of nodes in the network increases, the computations complexity for finding of minimum Steiner tree increases (Goldstone, et al., 2006).

Applications of the minimum Steiner tree concept in the real world are various. In the case where finding of a minimal network with the tree shaped structure is the goal, this concept can play a role(Goldstone, et al., 2006). Routing and designing of rail ways, airport layout, oil and water pipes are a few of the many examples of minimum Steiner tree application (Goldstone, et al., 2006; Herring, 2004).

2.4.3.2. Helbing et al.'s active walker model

Active walker models were proposed and developed in the 1990s by groups of researchers in the field of theoretical physics. This group of models has been used to describe filamentary complex systems in various physical and biological branches. Lam (1995) defined two types of walkers, an active and a passive walker. The passive walker is a walker which does not change its environment as it walks. In the contrast the active walkers change their environment during walking in the landscape and its movement is influenced by the changing environment.

Helbing et al.(1997) proposed an agent based model for the simulation of ant and human trail formation based on an active walker model. This model assumes that the walkers, move from their starting points to their destinations and continuously change the landscape by marking it. These markings can be done by chemical sign like pheromones in ant's trails or by physical signs like compacted ground and damaged vegetation in human trails.

In order to quantify the existing markings and the spatiotemporal distribution of them the ground potential concept was defined by Helbing et al.(1997).The ground potential G(r,t) expresses the ease and comfort of walking of a human being at position r at time t in the environment. So the trail has more potential to be formed in positions which have more ground potential values.

The attractiveness of an existing trail segment for the agent α at position of r_α at time t is defined in this model by the trail potential Vtr(r_α, t). When the trail potential's value increases, the tendency of the agent α increases to pass around that segment of existing trail.

The unit vector walking direction of the agent α as e_α (r_α, t) is the combination of the destination potential and the gradient of the trail potential. The travel direction of the agent α is influenced by two

main factors: the direct way to the know destination of the agent α and the attractiveness of the existing trail segment which is near the agent α.
At the beginning of the trail formation process pedestrians choose the direct direction to their destinations. After the formation of trails, pedestrians prefer to use (completely or partly) these existing trails as they are more comfortable and don't need to have physical efforts to form them.
The structure of trail system depends on the trail potential. If the value of trail potential is small and the near by trails have a little influence on the agent α, the direct way system will be formed. In case there is a large influence of a nearby trail on the agent α, the minimal way system will be formed. Helbing et al.(1997) defines the minimal way system as the shortest way system that connects all the starting points and destinations. However, in reality pedestrians prefer to have less detours, so the minimal detour system will be formed before the trail's growth reaches to the minimal way system structure. Figure 2.4 illustrates the simulation result of the trail formation between 3 points which was simulated by Helbing et al.(1997). The first picture (A) in Figure 2.4 shows the direct way system structure, the second one (B) depicts the minimal way system structure and the last one (C) shows the minimal detour system structure. Helbing et al.(1997) indicate that the minimal detour system is more similar to the actual trail structure and the realistic simulation can be archived if the model parameters are chosen realistically.

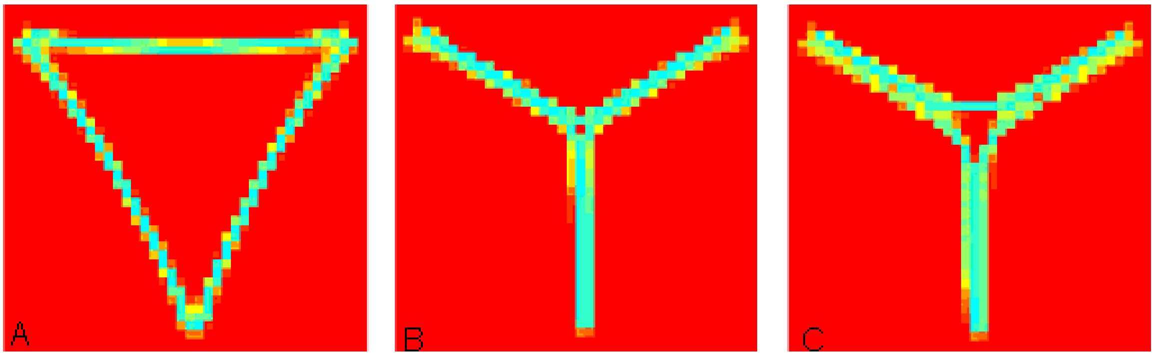


Figure 2.4: The simulation result of the trail formation between 3 points (Helbing, et al., 1997)

The active walker model tries to simulate the group behavior of human in the formation of paths. In the unbuilt plain surface, the first pedestrians try to build the direct paths. This selection is mostly based on the human logic that the direct path is the shortest path and this direct path can reach him/her to the destination with no risk. After the formation of paths, people tend to use previously built paths. Selection of the formed paths has social and physical reasons. Naturally, human prefer to pass from the more crowded paths to the paths which are empty of people. This desired crowd causes the passenger to feel more safe and ensures the passenger that the path will surely reach him/her to the destination. The previously formed paths have smoother and compact surfaces because of the frequent usage of the pedestrians. So, formed paths provide more comfortable physical situation for passing of new pedestrians.
After the frequent usage of direct paths, the eventual process of paths elements merging is observable. This process provides more feeling of safety in the pedestrians. Also this process ensure more comfortable physical situation for pedestrians as many pedestrians with different destinations use common paths in some areas. The bundling of elements of paths reduces the overall length of the paths system. This merging process continues until a suitable compromise situation will be formed between the overall length of the paths system and detour from the direct paths (which is not so much desirable for pedestrians).

One of the limitations of this model is that this type of model does not consider the different physical, economical and social factors as a trail growth driving forces.
This model was proposed to simulate the formation of trail in the plain and homogeneous ground like flat green areas in the public parks. So as it is assumed that the agent can walk everywhere in the plain environment and there is no physical obstacle in the landscape, the walking direction of the agent α is formulated based on this assumption. So if the agent is faced with a physical obstacle like a river, it is not guided to the alternative path to pass that obstacle.
Gilks and Hague (2009) extended the active walker model for the simulation of mountain trail formation.
The various social and economical driving force of trail formation are not entered to the model directly and in the disaggregate format.
In the Helbing et al.'s research it was assumed that if the trail is not used frequently, it will vanish because of the weathering phenomenon.
Footpaths can have a temporary existence in the informal settlement. They can fade because of different reasons such as building new buildings in the direction of the footpaths or seasonal swamps in the direction of it. So as it is obvious, weathering phenomenon is not the main driving force (espacially for the footpaths which area palced inside the settlment) of vanishing of trails in the case of informal settlement.
The walking direction unit vector of the agent α is influenced by the destination potential vector and the gradient of the trail potential vector in the proposed model. In the case that a nearby trail exists, the gradient of the trail potential vector increases in the combination. The unit vector of walking direction deviates the agent to the direction of existed trail.
As a result, the agent is made to pass over the centerline of the trail and this causes the trail to widen or to form new trails in the neighborhood of the existing trail. This can be true in some cases but most of the time people prefer to use the existing trail, especially when the distance of the agent is not too much from the centerline of the trail.
In addition, the model does provide an approach for studding of more complicated cases (such as existence of many trails in the neighborhood of the agent) for calculation of the influence of the different trail potentials on the agent and their respective unit vector of walking direction.
Also the active walker model tries to simulate the trail growth process in detail at a very microscopic level. This very microscopic level models the changes of the width of the trail along the way of the trail. But this level of the simulation is not the aim of this research, and this research will try to concentrate on the generalized modeling of infrastructure growth.

2.4.3.3. Minimum Steiner tree and human path formation

Goldstone, Jones and Roberts (Goldstone, et al., 2006) studied the group path formation behavior in forming of human trails. They used a software platform to simulate a virtual environment for tracking participant's movements between some known destination points. Participants can view a moment by moment movement of themselves and also behaviors of other participants. Their environment is constructed from a 100×100 grid. Each cell has a travel cost value. The cost value of each cell is decreased by passage of participants. In the other word, the ease of travel of each cell is increased by passage of participants from the cell. When the participant passes over each cell, the travel cost of other cells in the environment decrease according to a Gaussian distribution. To model the erosion of paths overtime, the model increase the traveling cost value of each cell gradually over time.
In this experiment, participants used the computer controls instead of walking in a real environment. So, as Goldstone et al. (2006) noted correctly, it cannot be overgeneralized their study results to more

realistic cases in the real world. However, some considerable results can be derived from Goldstone et al.'s experiment. Their study shows that there are some deviations from the beelines between destination points. The deviations from the beelines in this experimentt are mostly in the direction of forming minmum Steiner tree structure.So, Goldstone et al. named this diviations as "pro-Steiner deviations".

The formation of these pro-Steiner structures are matched with prior studies results which has shown that the indiviuals can find apromximate minimum Steiner tree formation for minimumization of the total length of network (Goldstone & Roberts, 2006).

Figure 2.5 illustrates the results of Goldstone, Jones and Roberts (2006) experiment for eight configuration of destination points. The brightness amount of each location in each configuration is proportional to the amount of passing times of participants from that location (Goldstone, et al., 2006). It is obvious in the first pair of configurations that the minimum Steiner tree structure forms more clearly in isosceles triangle than the equilateral triangle.

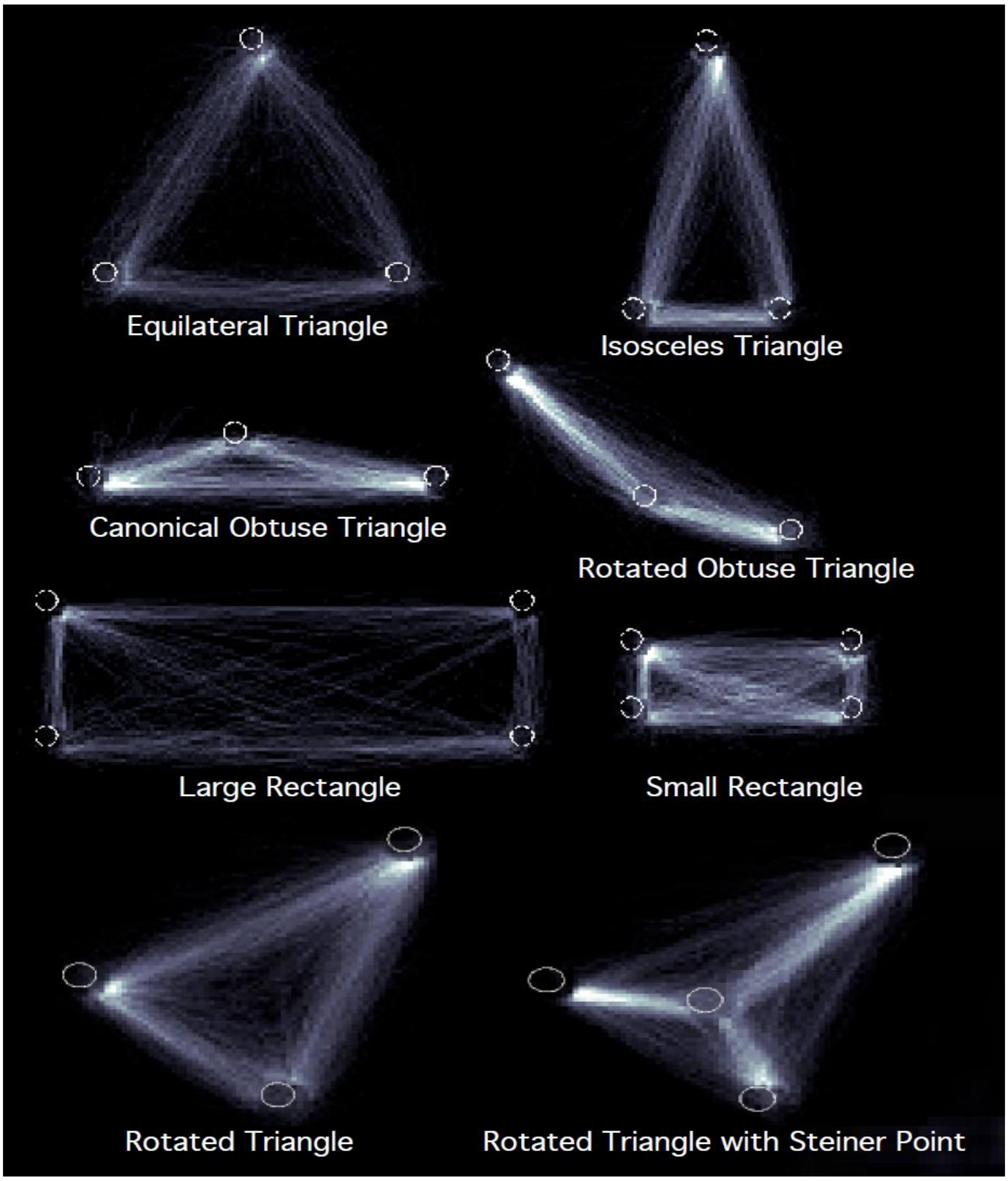


Figure 2.5: Results of Goldstone, Jones and Roberts experiment for eight configuration of destination points (Goldstone, et al., 2006)

The smaller angle of the top vertex in the isosceles triangle (in comparison with the same vertex's angle in the equilateral triangle) causes to increase of overlapping of deviated paths which intersect in this vertex. So, after some time a vertical path will be formed from the top vertex of the triangle towards the bottom of the triangle. This straight path is more attractive for other individuals and will be extended as more people pass from it overtime (Goldstone & Roberts, 2006).

In the second configuration there are two pair of triangles with the same obtuse 150 degree angles which are presented in two different orientations.

Figure 2.6 illustrates these two configrations of vertices. In the triangle ABC, as the vertex B has large obtus angle (150 degrees), as a result the A and C vertices have small angles (A+B=180-150). So, these small angels cause the increase of overlaping of deviated paths which intersect in these vertices. It is expected that the pro-Steiner structure will be formed over time but the experiment results are more similar to the minimum spanning tree.

The minimum Steiner tree (the solid line) and the minimum spanning tree (dash line) was drawn for two configurations of points in Figure 2.6. According to the obtuse angle of vertex B, it is observed that the length of the edge BS is small. Based on the small angles of A and C, it is observed that the length of the path ASC is approximately near to the path ABC (Figure 2.6). So, people are interested to use the direct path ABC more, which is the minimum spanning tree between these three points and near to minimum Steiner tree structure but with less detour from the direct path between A,B and C.

In the last configuration, the isosceles triangle is compared with the similar isosceles triangle with a Steiner point. The Steiner point in the second triangle plays the role of destination point. As it is obvious in Figure 2.5, when the Steiner point is available, people prefer to use it and travel from the paths with the Steiner structure.

Also, it can be concluded that in the absence of Steiner point, the group behavior of participants is towards the formation of pro-Steiner structure.

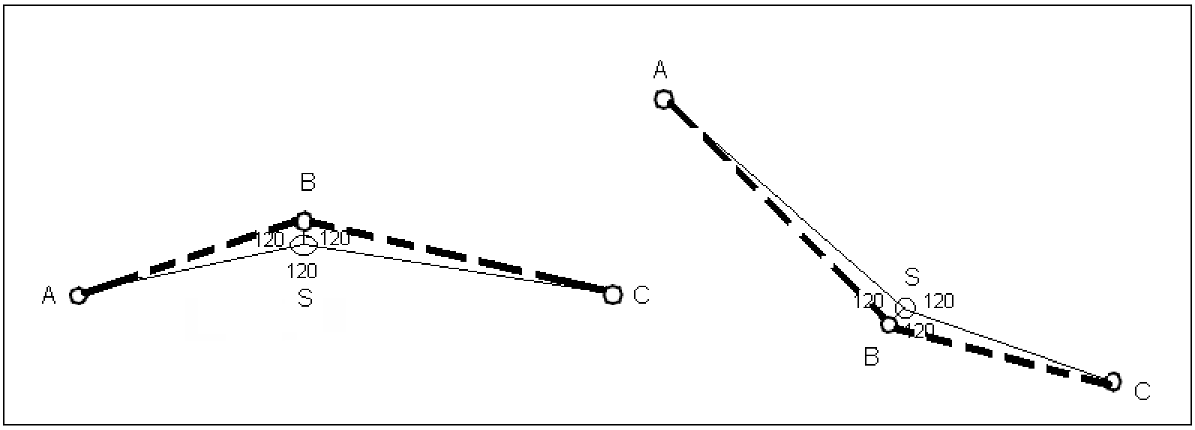


Figure 2.6: The minimum Steiner tree and the minimum spanning tree between three points with two different orientations (The minimum Steiner trees, the Steiner points, and the three edges 120 degree angles around Steiner points were drawn with exaggeration for better visualization of the problem)

Two rectangles with different scaling factor were used as the third configuration. Figure 2.5 shows that there is more tendency for individuals to form pro-Steiner structure in the smaller rectangle.

Figure 2.7 shows that the distance of AD and BC in the smaller rectangle is smaller than the similar distances in the larger rectangle. It is more probable that a passenger from A to D or C to B deviates from the beeline between these points in the larger rectangle (because of the existence of larger distances between these points). As the paths forms in the smaller rectangle near the diameters of the smaller rectangle, these diagonal paths deviate to their adjacent rectangle's edge and they will be used frequently by other individuals and the pro-Steiner structure will be reinforced by the frequently usage.

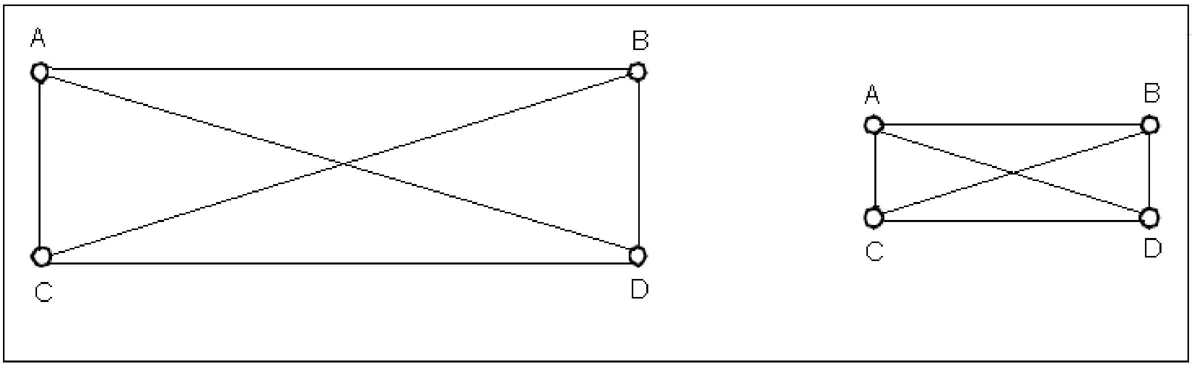


Figure 2.7: Two rectangles with different scale factors

2.5. Infrastructure hierarchy

Infrastructure is classified in to different categories to differentiate between different levels of infrastructure. There are different national and international standard systems (such as AASHTO, ASCE and PennDOT) for formal infrastructures classification. These classification systems classified formal infrastructure based on different criteria such as accessibility and mobility, width, longitudinal grade and pavement structure. There are some standards for trail classification. These standards were proposed by responsible organizations and sectors in different countries. Australian standard AS 2156.1, British standard (by British walking federation), the American standard (by US department of agriculture and forest service) and Canadian standard (proposed by different sectors like: Gros Morne national park and Cape Breton Highlands national park) are examples of the standards for trail classification (Arias, 2007).

The available standards for trail classification were mostly proposed for the formal paved footpaths in the urban areas or the footpaths in areas like national parks, forests or recreational zones. In all of these cases, trails have a side role in the movement of people in the transportation network.

In the following section AASHTO classification system will be explained as one the most commonly used infrastructure classification systems.

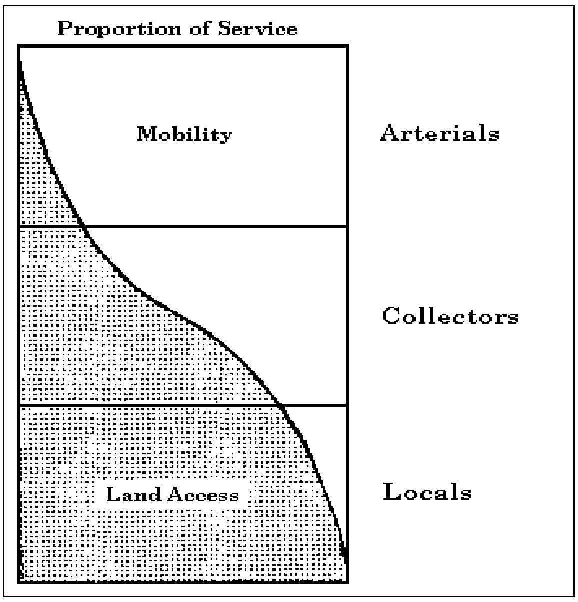
2.5.1. AASHTO classification system

AASHTO classification system classifies the road and highways based on the character of service they are intended to provide (AASHTO, 2001). This functional classification system categorized the infrastructure based on the role of road in the channelization of trips flow in transportation network. AASHTO classification system defined four functional systems in urbanized areas (Table 2.4).

Functional System	Description
Principal arterials	Carry the major portion of trips entering and leaving the urban area, and the majority of through movements desiring to bypass the central city. The significant intra-area travels, such as between central business districts and outlying residential areas, between major inner city communities, or between major suburban centers should be served by this system.
Minor arterial streets	Interconnect with and augment the urban principal arterial system and provide service to trips of moderate length at a somewhat lower level of travel mobility than principal arterials. This system also distributes travel to geographic areas smaller than those identified with the higher system. They contain facilities that place more emphasis on land access than the higher system, and offer a lower level of traffic mobility. Such facilities may carry local bus routes and provide intra-community continuity, but ideally should not penetrate identifiable neighborhoods.
Collector streets	Provide both land access service and traffic circulation within residential neighborhoods, commercial and industrial areas. Facilities on the collector system may penetrate residential neighborhoods, distributing trips from the arterials through the area to the ultimate destination. They also collect traffic from local streets in residential neighborhoods and channels it into the arterial system. In the central business district, and in other areas of like development and traffic density, the collector system may include the street grid which forms a logical entity for traffic circulation.
Local streets	The facilities not on one of the higher systems. Provide direct access to abutting land and access to the higher order systems. It offers the lowest level of mobility and usually contains no bus routes. Service to through, traffic movement usually is deliberately discouraged.

Table 2.4: AASHTO classification system for urbanized areas (AASHTO, 2001)

Principal arterials and minor arterial streets stress on a higher level of mobility instead of land access function for through movement. Local streets stress on the more land access function. And finally collector streets make a compromise between mobility and land access function (Figure 2.8).
Figure 2.9 schematically shows the functionally classified street network in an urbanized area.



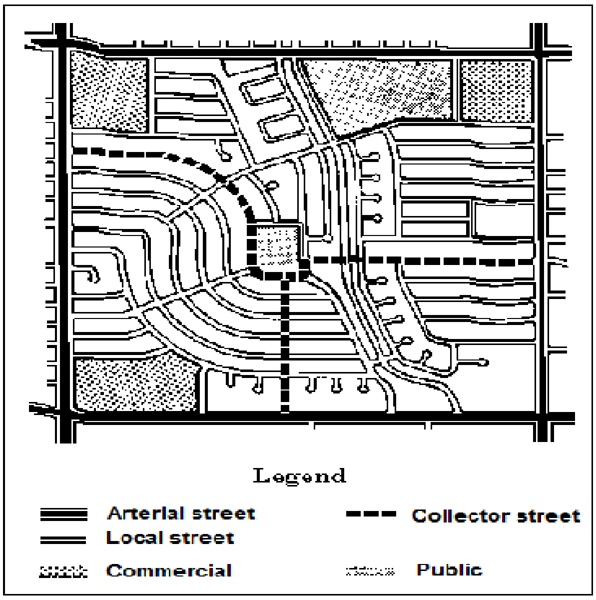


Figure 2.8: Relationship between the category of the infrastructure and land access and mobility function (AASHTO, 2001) (Right figure)

Figure 2.9: Schematic of functionally classified street network in an urbanized area (AASHTO, 2001) (Left figure)

2.6. Measurement of the complexity

The Euclidian geometry is not robust to describe the complex, rough and irregular geometry of objects in the nature. The researchers have paid attention to the new paradigm called fractal geometry for description of the complexity of objects and patterns in the real world in the recent decades.
The idea of defining a criterion for measuring of the complexity in the nature caused to develop a quantitative index called fractal dimension which is a fundamental concept in the fractal geometry.
Section 2.6.1 will review the concepts of fractal geometry and fractal dimension. In section 2.6.2, the application of the fractal concept in urban complexity studies will be discussed.

2.6.1. Fractals and the complexity

The term fractal first time was used by Benoit Mandelbrot in 1967 during his studies on the calculation of the British coastline length (Tang, 2003). He understood that similar patterns can be observed at different scales of study on coastline (Tang, 2003).
A fractal is a spatial object that has the irregular, scale-independent and self similar (if it is not strictly self similar it must at least be similar) geometry (Batty, 2005) and (G. Q. Shen, 2002) (Figure 2.10).

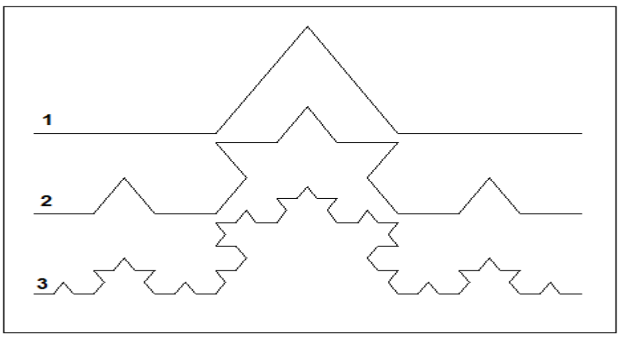


Figure 2.10: The iterations of the formation of the Koch curve as a fractal geometry (Bourke, 1991)

The fractal dimension concept has been developed by researchers for proposing a method for quantitative measurement of the complexity in an object or a pattern. The fractal dimension (*D*) is a value that quantifies of how completely a fractal emerges to fill space, as one zooms down to the fractal structure (Ginoux, 2009).

Fractal dimension (*D*) is a non integer value and lies between one (the dimension of the straight line) to two (the dimension of the plane) (van Raan, 1991). Studies show that the fractal dimension value increases when the complexity in the shape or the pattern increases.

There are different methods for calculation of the fractal dimension. Examples are the Calliper method, Box counting method and the Mass radius method (G. Q. Shen, 2002).

The Mass radius method and the Box counting method for calculation of fractal dimension are more popular in spatial analysis of non strictly self similar (not prefect mathematical fractals such as urban areas) fractals (G. Q. Shen, 2002).

2.6.2. Fractals and urban complexity

Fractal analysis is an effective and quantitative approach to describe the complex characteristics of geographical features (Tang, 2003).

As the similar or semi-similar actions and reaction of human has a considerable role in the formation of urban areas, it is expected that the similar patterns can be observed in the cities' morphology.

In the past decade, many researches were done to study the feasibility of using the fractal concept to study the irregular morphology of cities and their sub systems (Tang, 2003).

Batty & Longley (1994) and Batty & Xie (1996) were some of the first researchers that studied the fractal properties of cities. They studied the fractal dimensions of various urban areas. In their researches they studied the relationships between fractal dimension with other city properties (such as size and form and population distribution) in the urban growth process. Their studies indicate that as the urbanisation process has been developed in the area, the fractal dimension of the urban pattern in the area increases. The results of their studies show that the fractal dimension of more mature and more urbanised areas is higher than younger and less developed urban areas.

Other researchers like Appleby (1996), Sambrook & Voss (2001) and Voss (2001) and Shen (2002) continued the study on the using of fractal concepts in urban pattern and characteristic studies.

The irregular morphology and the organic growth of transportation networks as a sub system of cities have attracted the attentions of researchers since the past decade (Sun, Jia, Kato, & Hayashi, 2007)

Sun et al (2007) divided these studies in to the two main categories. The first category of studies (such as: (Benguigui & Daoud, 1991) and (Rodin & Rodina, 2000)) has been focused on revealing the self similarity of transportation systems.

In the other category, the studies have been concentrated on the fractal properties of the transportation networks and their relationship with urban functions and properties (such as: (Chen & Luo, 1998), (G. Shen, 1997)and (Tang, 2003)) .

2.7. The other used concepts

2.7.1. Synthetic population

For proposing of the microscopic simulation, the micro data is needed. The micro data of population sometimes are not available or uncompleted or suppressed by administrative registers because of the personal data privacy preserving laws. Therefore, the application of the synthetic population data generation methods are popular for retrieving of disaggregate population data from the general accessible aggregate data (Moeckel, Spiekermann, & Wegener, 2003).

The disaggregated data for the household such as size and income and the age and the sex of the household members are generated.
The new methods for generating of the synthetic population are mainly developed for improving the accuracy of synthetic population generation.
The different methods are existed for the generation of synthetic population data, including the techniques like: geodemographic profiling ,stratified sampling, data merging, data fusion, iterative proportional fitting, reweighting, synthetic reconstruction and their combinations (Z. Huang & Williamson, 2001).

2.7.2. Activity based travel modelling

Activity based models increasingly are used as a popular approach for travel demand analysis.
These models focus on generating of individual's travel patterns in the disaggregate approaches.
The activity can be described as a physical participation of an individual in action which satisfies his/her goals and requirements. The activity is formed based on the sociological, economical and physiological needs of a person. For doing most of the activities, a trip must be done.
The theoretical study on the activity based travel demand models is started by Hägerstrand (1970) and Chapin (1974) . These studies shifted from the trip based, aggregated travel prediction models to the new approach of activity based, disaggregated prediction models.
Activity based travel demand models predict which activities are done at what time and destinations trips and the schedule and destinations are predicted in this type of models (Jovicic, 2001).
The individual is a decision maker who faces with a large choice set of different activity patterns in the time-space domain (Zhang & Levinson, 2004)
The household roles and his particular lifestyle, the household options on activity type and the location , time and budget constraints are some of the parameters which influence on the decision making process of an activity performance.
Jovicic (2001) mentioned to the five fundamental paradigms which the activity based travel demand models rely on them. First, in these models the travel is originated from the activity participation. Second, these models focus on the sequences of activities. The third fundamental basis is that the activities are planned and executed in the context of the household. The fourth basis is that the activities are spread along the time in a continuous manner. And finally, the travel choices are limited in time and space, and by consideration of individual limitations in these models.
Some studies have been done on the activity based travel demand models in these years, however, there is still much potential for improvement of these models based on the understanding the characteristics and dynamics of individual's travel behaviours.

3. Analysis of Informal Infrastructure Growth Driving Forces and Characteristics

3.1. Introduction

The first part of the chapter will describe the study area, data that were used for the analysis and the data preparation performed in order to make the analysis possible.
In the second part of this chapter the results of the different analyses will be discussed. These analyses were performed to determine some of the driving forces (factors) and characteristics of informal infrastructure growth in Dar es Salaam. Idea behind this is that a process (combination of factors) will result in a certain (spatial) pattern. By analyzing this pattern inside can be gained in the factors that contribute to the informal growth of infrastructure in the informal settlement.

3.2. Study area

Kinondoni district is the northernmost of three districts in Dar es Salaam, Tanzania. This district is broken into 4 divisions, 27 different wards, and 113 sub wards. Most of the settlements in Kinondoni are informal settlements.
A part of Kinondoni district was selected as the case study area. The study area includes Ubungo, Sinza, Manzese, Mabibo, Tandale, Ndugumbi, Makurumula, Mburahati, Kigogo, Makumbusho, Magomeni and Mzimuni ward in Kinondoni district (Figure 3.1).
This study area was chosen because of the following reasons:

- It is a good example of an informal settlement in Dar es Salaam
- It has been a study area for the Department of Urban and Regional Planning and Geo-Information Management of ITC for many years and for this reason a lot of data are available
- The area has gone through different steps in its development and has now reached a more or less permanent stage
- Existing housing model focuses on part of this area

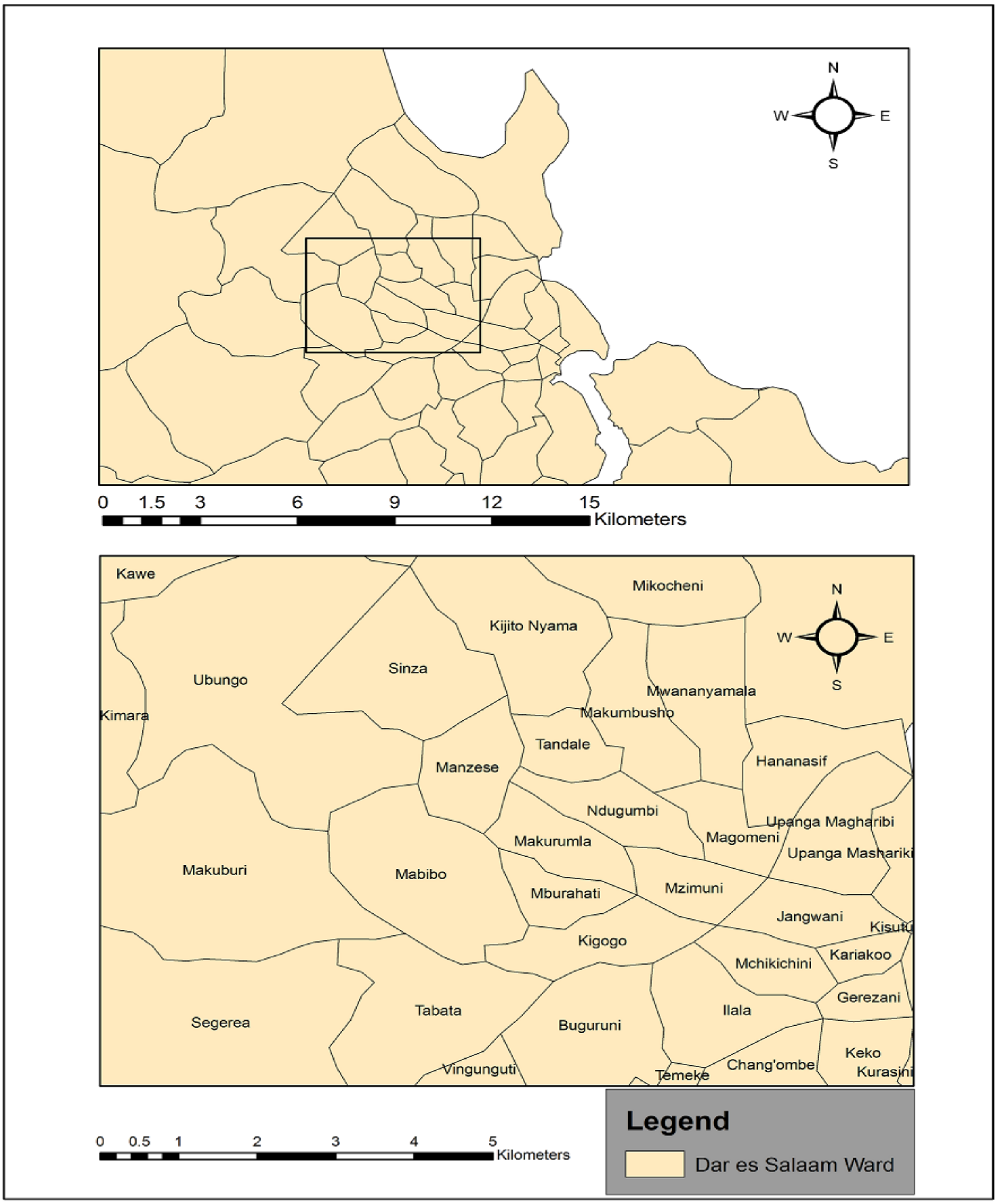


Figure 3.1: The case study area

3.3. Data Overview

The data used for these analyses were received from Dr. Richard Sliuzas (Department of Urban and Regional Planning and Geo-Information Management of ITC). Data were collected over a period of 40 years. Data show a large diversity because they were collected over a long period of time and were collected by different people and for different purposes. Table 3.1 gives an overview of data which are used in this chapter.

Data	Type	Date	Format
Road	Line	2006	.shp
Footpath	Line	2006	.shp
River	Line	1999, 2001	.shp
Swamp	Polygon	1999	.shp
D.E.M	Raster	1999	.tif
Orthophoto	Raster	2002	.tif

Table 3.1: An overview of data which are used in this chapter

3.4. Data Preparation

The datasets used during the analyses showed different kinds of problems that had to be prepared before performing the analysis. Section 3.4.1 to 3.4.3 will give an overview of the types of problems formed in the data and the way they were solved.

3.4.1. Inconsistent map extent

To approach this, the available different infrastructure layers in the Dar es salaam dataset were studied and the relevant data layers were selected. Some of these layers consisted of only a part of the study area.

3.4.2. Missing features

The relevant available data layers were merged and tried to digitize the missing features based on the available digital image of the study area for providing the maximum coverage of essential data in the study area.
Some types of infrastructure data and river layer were not available for coverage of all parts of the study area. These features were digitized based on the available digital image of the study area.
Another similar problem occurred for the flood zone data. This data was extracted from the DEM layer based on the height of the flood prone areas.

3.4.3. Geometrical problems

One of the most important problems faced was understood in infrastructure layers. Because the road centerlines were derived from a polygon layer and also digitizing errors, gaps existed between the different infrastructure types. This problem required the following pre-processing.
The geo-database for the infrastructure was built based on four classes of infrastructures in the study area. The topological errors (such as under shooting and over shooting errors) of the data layers of the geo-database were solved.

3.4.4. Slope layer production

The slope layer of Dar es Salaam was produced based on the available digital elevation model (DEM) raster (with 10mx10m pixel size) in the data set.

3.4.5. Infrastructure classification

The assumption is that the infrastructure in the informal settlement is not the result of one process but in fact is the result of multiple processes at different scales and in different time periods. Approach taken for the analysis was to divide the total infrastructure into four specific classes and to analyze

these classes separately. The expectation is that the comparison of the analysis results of these four classes can reveal difference in processes that have caused the different levels of roads.
The following sections will explain:

- Classification system that is applied for this study including:
  - The philosophy behind this classification system and why it is suitable for the informal settlements
  - The criteria applied to classify the roads

3.4.5.1. Infrastructure classification system for the informal settlement

The infrastructure in informal settlement can consist of formal infrastructure and informal infrastructure. The formal infrastructure can be paved or unpaved roads. The formal infrastructure can be built directly by the government or they can be upgraded trails which were formed in the bottom up process by human.
As the main goal in this research is to study informal infrastructure, all four types of formal roads (based on AASHTO classification system) are called formal infrastructure in this research.
Human made trails in the urban infrastructure network have irregularity and variation in the shape and width. As there is no formal classification system available for the trails in the urban infrastructure network, a descriptive classification system is defined in this research based on AASHTO classification system concepts. However, more comprehensive studies will be needed to propose a classification system for categorization of trails in informal settlement.
Three classes of urban trails are defined in this research for the classification of trails (Table 3.2).

Functional System	Description
Collector trails	Collector trails make a compromise between mobility and land access function. They collect the traffic from local trails and connecting them with formal arterials (principal and minor) and collector streets.
Local trails	Local trails penetrate between building blocks. They have a more accessibility function and pass the travels to the collector trails or formal arterials (principal and minor) and collector streets.
Personal trails	Personal trails consist of all trails not defined as collector s or locals. They provide the most direct access to land and buildings with little through movement (mobility). They can pass the travels to collector and local trails and also formal arterials (principal and minor) and collector streets.

Table 3.2: Proposed classification system for categorization of urban trails in the informal settlement

The trails are built by human in the bottom up process but they can be used by vehicles too.
This situation can be seen in Dar es Salaam as the number of vehicle users have been increased in the recent decades. As the level of the trail increases from personal to the collector trails, the possibility of trail usage by vehicles is increased.

3.4.5.2. Infrastructure classification in the study area

The infrastructure in the dataset was classified into two general classes: road and footpath. In this study the infrastructure was categorized in to the four specific class of infrastructure (formal infrastructure, collector trail, local trail and personal trail) based on the pre-defined infrastructure classification standard for informal settlement (Figure 3.2).

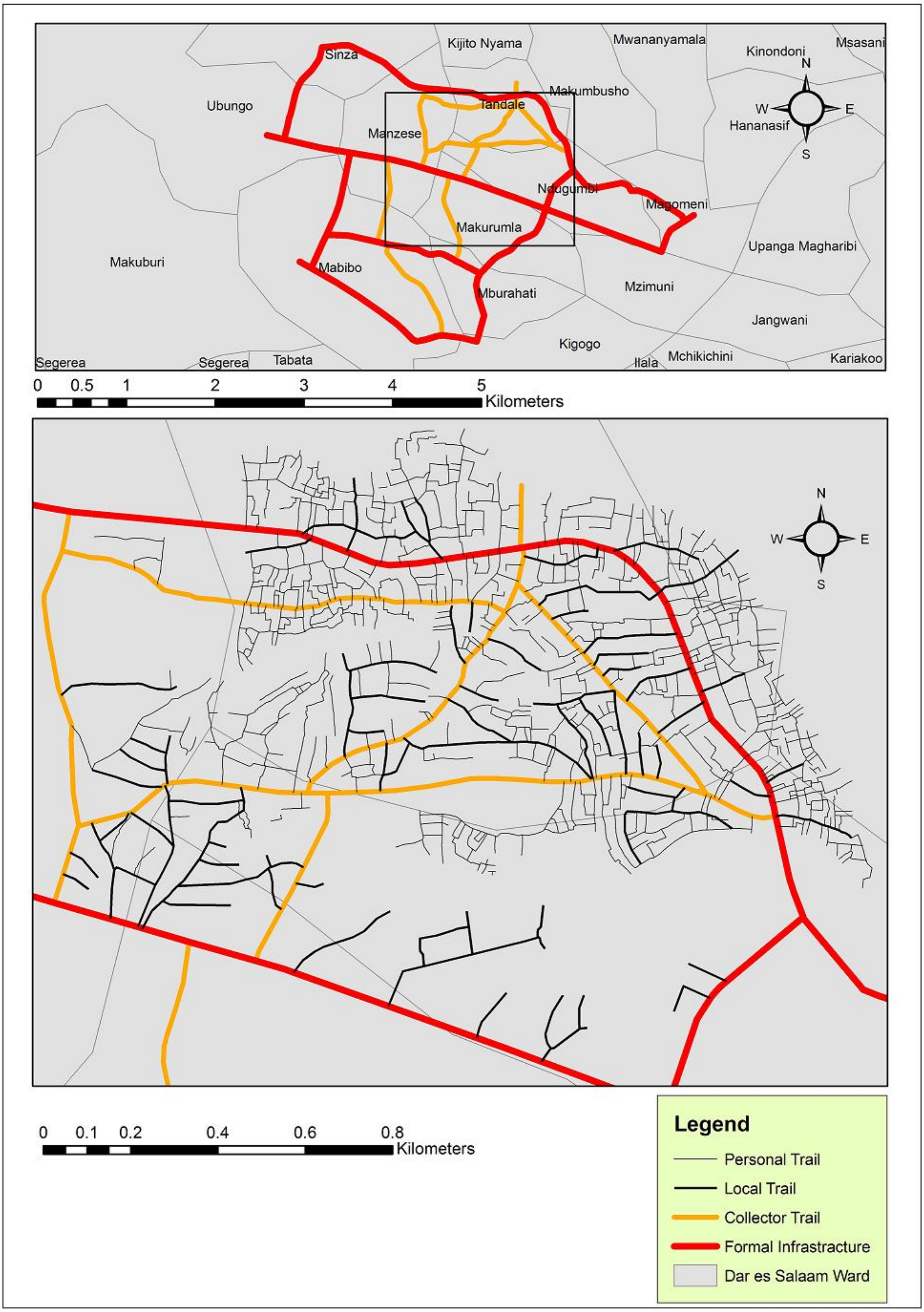


Figure 3.2: Infrastructure classification in the study area

3.5. Data analysis

The ultimate purpose of performing these analyses is to reveal the factors that together form the process behind the informal growth of the infrastructure in Dar es Salaam.

As explained before, it is not expected that there is only one driving mechanism behind the process of infrastructural growth but in fact we are looking for a complex set of factors that together resulted in the spatial pattern of the infrastructure. One of the assumptions is that infrastructure has hierarchical levels. Four different classes of roads were identified and all analysis will be performed for each class separately. Results of the different classes of roads will be compared to identify different growth mechanisms.

The factors that influence the growth pattern were subdivided into three categories:

- Relationship between infrastructure and environment
- Geometric relationships in infrastructure
- Relationship between buildings and infrastructure

3.6. Relationship between infrastructure and environment

The environment influences the growth of infrastructure in different ways. For these analyses two different ways were selected: Topography and barriers.

Topography influences the infrastructure pattern. The infrastructure avoids passing from the steep slope. For the less steep slopes, it can be often seen the infrastructure pass from the certain range of slope degree.

It is obvious that there can be barriers that influence the growth of infrastructure. It is not easy to cross a river, steep valley and swamp. So, this type of feature has an impact on the infrastructure in its vicinity.

For the situation of Dar es Salaam four different types of environmental factors of slopes, rivers, swamps and flood zones were identified and analyzed.

3.6.1. Topography

- **Hypothesis:**

Lower level of infrastructure (personal trail) in the trail classification hierarchy can cross from the steeper slopes (in the comparison with the higher level of infrastructure).

- **Approach:**

Finding of the maximum slope of trails per infrastructure type.

- **Methods:**

Two methods are applied for finding the maximum acceptable slope of each type of infrastructure.

In the first method, each type of infrastructure was converted to its former vertices (as points).

In the second method, each type of infrastructure in the data set was converted into equidistant points (with 1 meter intervals).

After that, the slope value of each point was extracted and the maximum slope for each point per class of infrastructure was derived via both methods. Finally the results of the maximum slopes in the four infrastructure classes were compared.

- **Results:**

The results of the first and the second method are illustrated in the Table 3.3 and Table 3.4.

As the digital elevation model (DEM) raster has 10mx10m pixel size, the accuracy of the slope layer as the output is decreased (in comparison with the slope layer which is produced from the DEM raster

with the smaller pixel size). In order to achieve more realistic slope values of points, the interpolation was done for each point based on the slope of adjacent cells.
In the first method, as the vertices of each type infrastructure layer were not distributed in some part of the infrastructure, some of the slope values for each type of infrastructure were not collected.
But as the second method, was sampled the slope values of each type of infrastructure with equal distances, the results of this method extract more sample slope values than the first method. So the maximum slope values for each type infrastructure in the Table 3.4 are accepted in this study.

Type of Infrastructure	Maximum Slope (Degree)	Number of Points
Personal Trail	12.77	3785
Local Trail	9.48	314
Collector Trail	9.69	149
Formal Infrastructure	7.56	186

Table 3.3: Maximum slope per each type of infrastructure based on method one

Type of Infrastructure	Maximum Slope (Degree)	Number of Points
Personal Trail	14.54	31176
Local Trail	12.49	8087
Collector Trail	10.22	8751
Formal Infrastructure	8.87	19380

Table 3.4: Maximum slope per each type of infrastructure based on method two

- **Discussion:**

Both methods show the same pattern of the highest slope for the personal trails and the lowest slope for formal infrastructure. However the maximum slope values in the second method is a little larger than the first method.
The lowest level of infrastructure (personal trail) is built adjacent to the buildings to provide the residents accessibility to higher levels of infrastructure. So, the location of the personal trails has a tight dependency to the location of construction of the buildings. As the residents compete to build their buildings in the better areas (like: far from swamps and flood risk areas), they buildings might be built in higher slopes (but far from the mentioned negative parameters). As the level of infrastructure increases to the highest infrastructure hierarchy (formal infrastructure), and the accessibility function of infrastructure decreases (and the trail direct relationship with buildings decreases) the maximum acceptable limit of infrastructure slope decreases. In the highest level of infrastructure planers attempt to avoid the steep slopes in the designing process of formal infrastructure. However when they face with unavoidable steep slopes they try to change the topography of the area to decrease the steep slopes.

3.6.2. Suitable trail's slope:

Steep slope make a difficulty for the pedestrians to walk stably and firmly and also with less physical effort. This is because of the force which is equal to mg*sin α is exerted to an object with a mass of m in the opposite direction of its passage in the uphill direction (Figure 3.3). So, passing from the steep slopes in the uphill direction is harder and needs to consume more energy to resist against the more surface parallel force of mg*sin α . Also in the downhill direction as the degree of slope increases possibility of the easy, firm and stable walking is decreased.

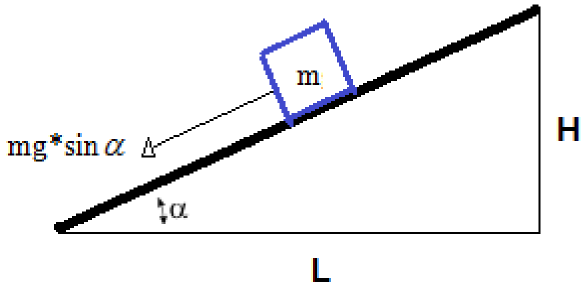


Figure 3.3: The surface parallel force which is exerted to an object on the slope.

The increment in the degree of the slope increases the hardness of the slope climbing (walking on the slope). This increment shows a nonlinear trend. For example the hardness of climbing from the slope of 90 degrees is not two times harder than the slope of 45 degrees. The hardness of climbing from the right angle slope is an infinite in comparison with the 45 degrees slope.

As the urban trails are used frequently by different types of pedestrians (different age and sex), the suitable range of the degree of slope for pedestrian walking in the urban trails is a limited range.

Portland Parks & Recreation Trail Guidelines (2009) suggest the maximum suitable trail's slope (which the pedestrian can walk stably, firmly and easily) as 5% (2.86 degrees) for any trail segment length, 8.33% (4.76 degrees) for the maximum 50 feet (15.24 meters) trail segment length, 10% (5.71 degrees) for the maximum 10 feet (9.14 meters) trail segment length and 12.5% (7.12 degrees) for the maximum 30 feet (3.04 meters) trail segment length. However other literature like the NBST (2002) and Martin (2004) study defined the slope of 10% (5.71 degrees) as the maximum suitable trail's slope (without the consideration of the trail segment length).

The hardness of climbing from the slope is increased with the non-linear (like exponential function) trend when the degree of the slope increases. So, the hardness of walking on the gentle slopes is not so much different for the pedestrian. The pedestrian can walk easily on the slopes with the slope degrees under the maximum suitable slope degree without any preference. As the slope of the area increases and exceeds more than the maximum suitable slope degree, the pedestrian more prefer to minimize the length of passage or avoid passing from this area.

The residents of informal settlements accustom to live in the more difficult condition of living than formal urban areas residents. So, it is expected that the trail can pass from the steeper slopes in the informal settlement in comparison with the trail in the formal settlement.

- **Hypothesis:**

The amount of the maximum suitable trail's slope degree for local and collector trail is equal or more than 5.71 degrees (slope of 10%).

- **Approach:**

To find the suitable trail's slope degree range for local and collector trail.

- **Methods:**

Contour lines were created based on the slope layer. These contour line shows the locations that have the same slope value. The different contour lines were generated with the different contour interval values in each iteration. In all of the iterations the base contour value was defend as 0.

The ArcGis software creates the contour lines based on the input surface with an interpolation of the input surface values. For example when the contour map was produced with contour interval value of 4, the contours lines with the value of 0, 4.5, 9, 13.5 etc. were produced. For instance, the area between 0 and 4.5 contour lines (include 0 contour line but not include 4.5 contour line) contain all of the locations in the area which have slope degree values equal or more than 0 but less than 4.5 degrees. So, the entire slope degrees less than 4.5 are categorized in the same category. The slope contour maps with the contour intervals of 4.5, 4.7, 5, 5.5, 6, 6.5, and 7 were produced.
The slope contour maps were overlaid with the local and collector trail layers one by one. As the goal is finding the range of suitable trail's slope degree, the condition of each types of trail was studied according to the contour lines.
For example if the hypothesis is that 4.5 is the maximum suitable trail's slope degree in a specific type of trail, the contour map with contour interval value of 4.5 is overlaid with that type of trail. To study this hypothesis the condition of the specific types of trail are studied according to contour lines with the value of 4.5. The criteria for finding the maximum suitable trail's slope degree is that the majority of trails in each trail layer should be stopped near the contour lines with the value equal to the contour interval (in this example: 4.5). Also the majority of the trails in each type of trail should placed in the area between 0 contour line to the contour lines with the value equal to the contour interval (in this example: 4.5). The trial and error process was done to find the best suitable slope range which fulfills the defined criteria to find the maximum suitable trail's slope degree.
To study the percentage of the infrastructure (from each type) which is placed in the higher slope degrees than maximum suitable trail's slope degree, the data set was converted into equidistant points (with 1 meter intervals).
The number of points which were located in the steeper slopes than maximum suitable trail's slope degree was calculated. Finally this number was divided to the total number of sample points in each type of trail.

- **Results:**

The contour map with the contour interval value of 6 is selected for both local and collector trails (Figure 3.4 and Figure 3.5). So the maximum suitable trail's slope degree for local and collector trails is equal to 6 degrees.
The Table 3.5 and Table 3.6 show the percentage of the local and collector trails which were placed in the slope degrees more than the defined degree.
The percentage of the local and collector trails which is placed in the higher slope degrees than maximum suitable trail's slope degree (6 degrees) are 4.41% and 1.39 % respectively.

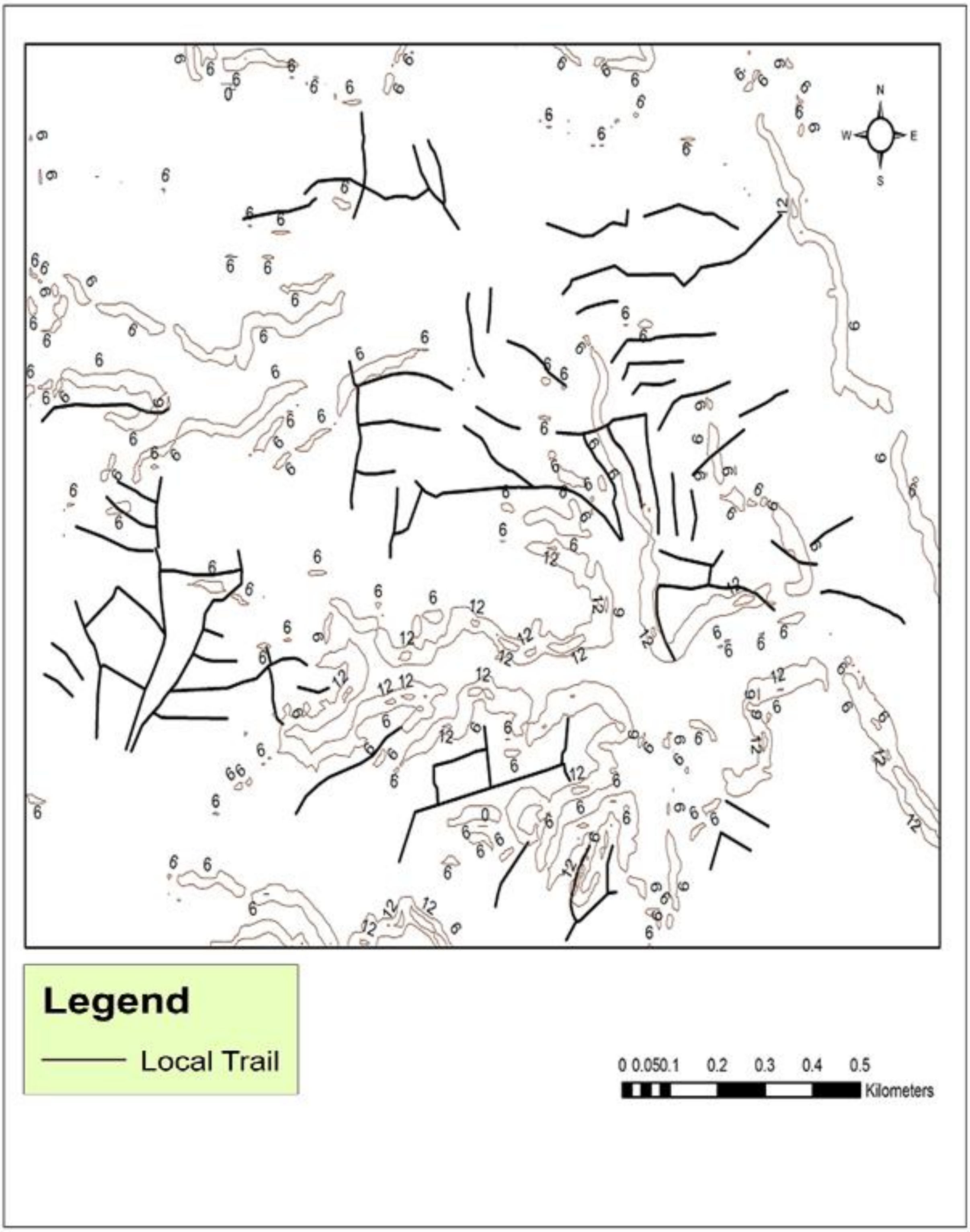


Figure 3.4: The map of local trails with the contour interval value of 6

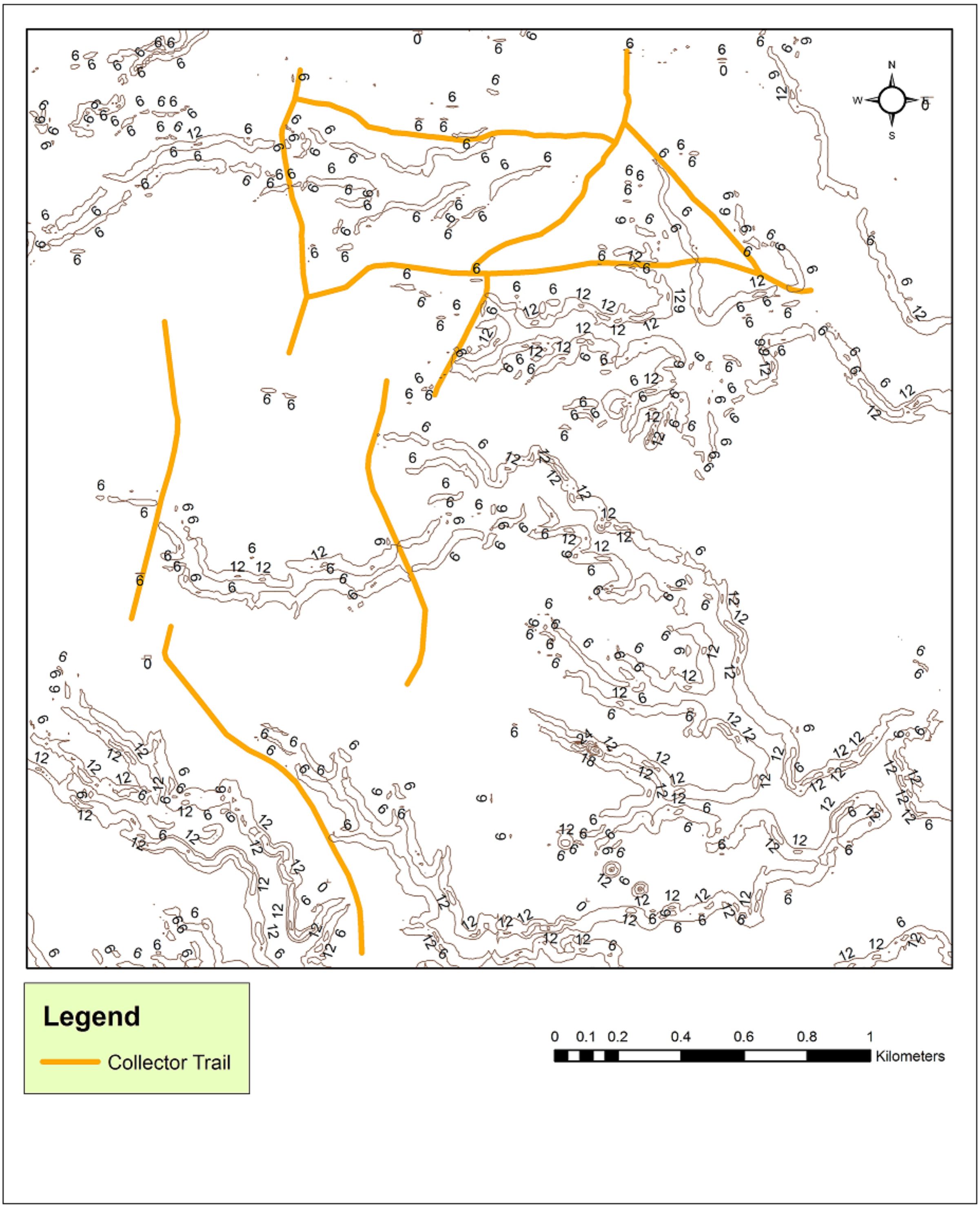


Figure 3.5: The map of collector trails with the contour interval value of 6

Slope (degree)	Percentage
More than 4	12.25
More than 4.5	9.81
More than 4.7	8.73
More than 5	7.33
More than 5.5	5.68
More than 6	4.41
More than 6.5	3.59
More than 7	2.72

Table 3.5: The percentage of the local trails which were placed in the slope degrees more than the defined degree

Slope (degree)	Percentage
More than 4	9.23
More than 4.5	5.75
More than 4.7	4.85
More than 5	3.42
More than 5.5	2.06
More than 6	1.39
More than 6.5	0. 89
More than 7	0. 45

Table 3.6: The percentage of the collector trails which were placed in the slope degrees more than the defined degree

- **Discussion:**

According to what was mentioned before as the contour interval is increased, the range of the suitable trail's slope degree is increased. Figure 3.6 and Figure 3.7 show the condition of local and collector trails in a part of the study area with the contour interval of 4.5 and 6.

The range of the suitable trail's slope in the Figure 3.6 and Figure 3.7 is 4.5 and 6 degrees (right and left picture).

In the case that the suitable trail's slope is equal to 6 degrees (the locations where placed on or between the 0 to 4.5 degree contour lines), more trails segments pass from the locations which placed in the suitable trail's slope range.

As it was mentioned before, the personal trail is built adjacent to the buildings so the location of it has a tight dependency to the location of building of the buildings. This fact causes that this type of infrastructure is built in all of slopes where the buildings can be built (which is equal to the maximum possible slope of the personal trail which was calculated in the previous section) to provide their accessibility.

As the level of infrastructure increases to the higher infrastructure hierarchy (local to collector trail), and the accessibility function of infrastructure decreases the maximum acceptable limit of infrastructure slope decreases. So, the percentage of the local trails which were placed in the slope degrees more than the 6 degree is more than its similar percentage value in collector trails.

Figure 3.6: The condition of local trails in a part of the study area with the contour interval of 4.5 and 6 (right and left picture respectively)

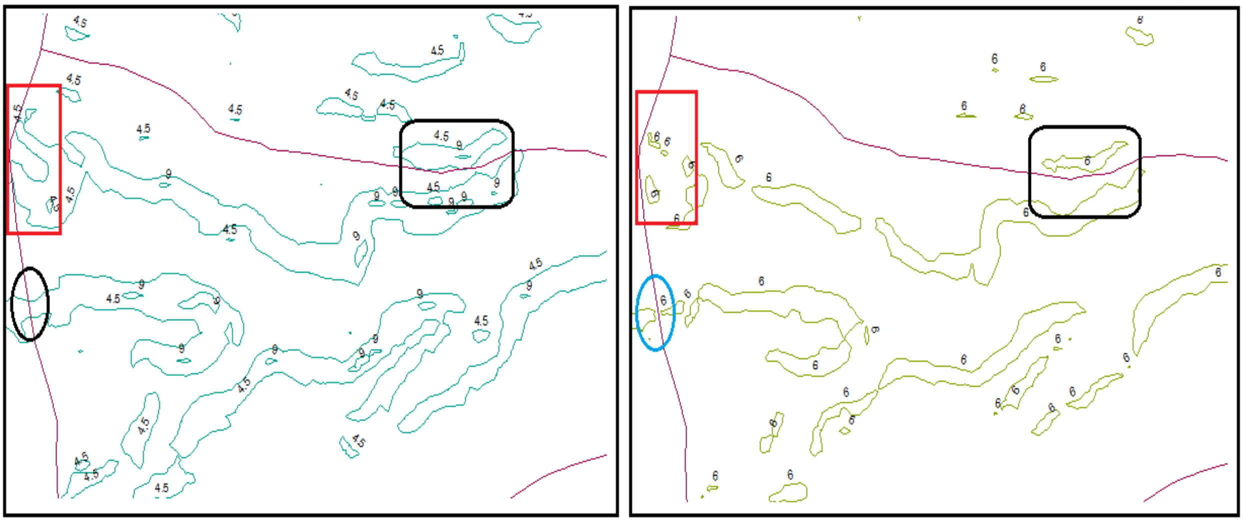


Figure 3.7: The condition of collector trails in a part of the study area with the contour interval of 4.5 and 6 (right and left picture respectively)

3.6.3. Barriers

3.6.3.1. Pre- built buildings and the protected lands

Pre- built buildings and the protected lands behave as an obstacle for the growth of infrastructure.
One of the typical Swahili housing pattern is that the house owners build a small building beside the main building (the large house) of the house (Sliuzas, 1988). In this case the infrastructure cannot pass from the space between these large and small building as they are parts of one house and they have a same ownership.

3.6.3.2. River

- **Hypothesis:**

The higher levels of infrastructure can pass from the rivers (by bridges). The lower levels of infrastructure do not pass from the rivers.

- **Approach:**

Determine if intersections exist between the infrastructure and the river.

- **Methods:**

The attribute table of each type of infrastructure was appended to the attribute table of the river layer by spatial join tool in ArcGis software. The intersection option was chosen as the criterion to match rows. This option matches rivers that intersect each types of the infrastructure. The attribute table of the output of the analysis was studied if there is an intersection between each type of infrastructure and the rivers in the analysis study area by getting the query from the spatial join attribute table. The non crossing (from the river) types of infrastructure were studied to find the minimum distance of that type of infrastructure from the rivers. This was done by using of the spatial join tool and matching the infrastructure to the closest river.

- **Results:**

The formal infrastructure and collector trails pass from the rivers in the analysis study area in some areas. The local and personal trails do not pass from the rivers and stop in the certain distance where ever they face with the rivers (Figure 3.8).
The minimum distance of local trails and personal trails from their adjacent rivers are 95 cm meter and 13 cm respectively.

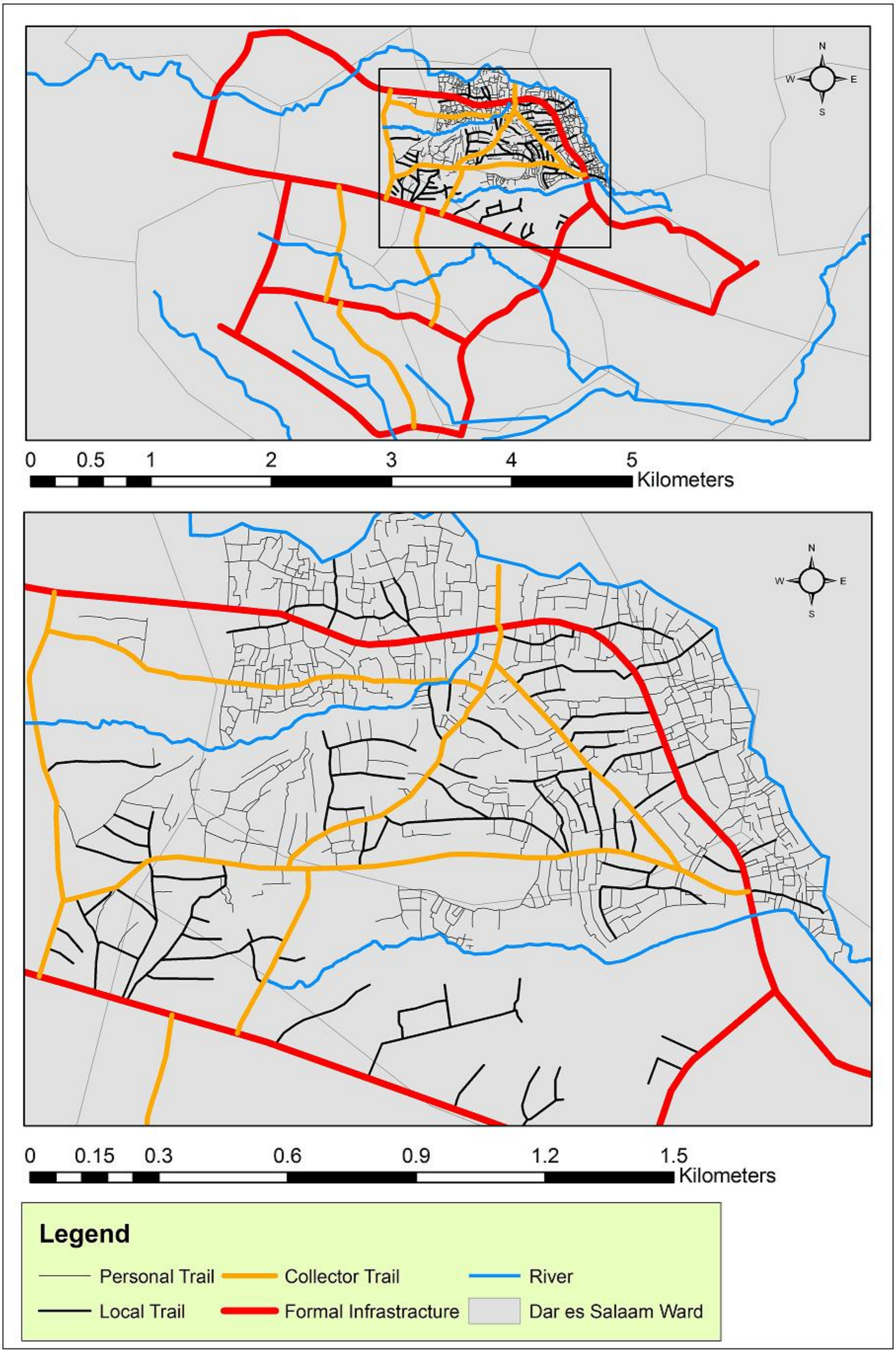


Figure 3.8: Map of rivers in the analysis study area

- **Discussion:**

The higher levels of infrastructure (formal infrastructure and collector trail) are used by many passengers and collect the trips of lower levels of infrastructure and conduct them to the destinations. As the main role of the higher levels of infrastructure is the mobility function they pass the rivers (in the cases that the river has a narrow width or has a flood channel functionality) to make the possibility of reaching to the all destinations for all of the passengers in all parts of the area.
Where ever the higher levels of infrastructure (formal infrastructure and collector trail) want to pass from the river, the bridge can be built on the river as these types of infrastructure play the most important role for reaching to the far destinations in the area.

3.6.3.3. Swamp

- **Hypothesis:**

All types of infrastructure don't pass from the swampy areas.

- **Approach:**

Checking each type of the infrastructure if it passes from the river.

- **Methods:**

The attribute table of each type of infrastructure was appended to the attribute table of the swamp layer by spatial join tool in ArcGis software. The intersection option was chose as the criteria to match the rows. This option matches swampy areas that intersect each types of the infrastructure. The attribute table of the output of the analysis was studied if there is an intersection between each type of infrastructure and the swamp in the analysis study area by getting the query from the spatial join attribute table. The types of infrastructure which were recognized non crossing (from the swamp) infrastructure were studied to find the minimum distance of the infrastructure from the swamp. This was done by using of the spatial join tool and matching the infrastructure to the closest part of swamp boundary.

- **Results:**

All types of infrastructure don't pass from the swampy areas (Figure 3.9). The minimum distance between all types of infrastructure from the boundary of the swampy area belongs to the personal trails with the distance of 1.65 meters.

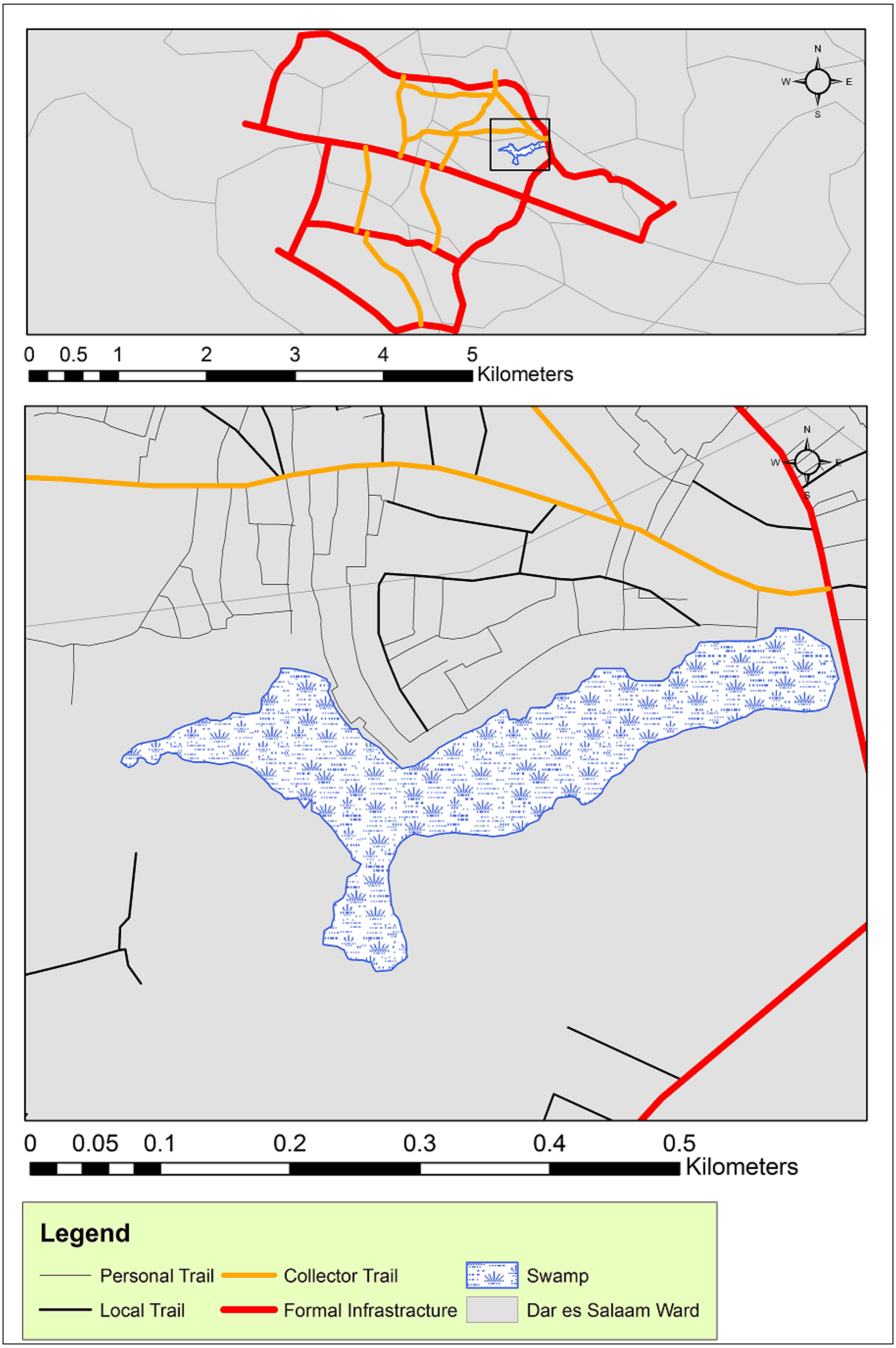


Figure 3.9: The map of swamp in the analysis study area

- **Discussion:**

As walking in the swampy areas is very hard for pedestrians and requires an expensive engineering operation if the formal infrastructure wants to pass from swampy areas, no infrastructure pass from the swamps.

3.6.3.4. Flood zones

- **Hypothesis:**

The infrastructure has a different pattern in the flood zones.

- **Approach:**

Comparison of the infrastructure pattern in the flood prone area with non flood prone area.

- **Methods:**

The fractal dimension for the infrastructure network of two areas in the study area was calculated. The first area is placed in the flood prone area and the second area is placed in the non flood prone area. The fractal dimension values for the infrastructure of these two areas were calculated by the box counting method in ImageJ software.
The trial and error method was used to define the suitable covering box sizes. This trial and error process is because of omitting the redundant cases with the different box size values but with the same number of boxes which are required to cover the object (count). This is lead to fit proper line on the graph with logarithm of box size values on the horizontal axis and logarithm of count values on the vertical axis. So, this approach causes to calculate the correct value of fractal dimension as slope of this graph.
Finally the fractal dimension values of the infrastructure in two areas were compared.

- **Results:**

The fractal dimension indicates about the morphology of the road networks and how they are developed. As the infrastructure network has been developed, the fractal dimension will increases. The fractal dimension of the infrastructure in the developed urban areas in some U.S cities is around 1.7 (Sun, et al., 2007). The fractal dimension of the infrastructure in the flood prone area and non flood prone area is 1.49 and 1.47 respectively (Figure 3.10 and Figure 3.11).
The small difference between these two values shows that there is little difference in the morphology and pattern of the infrastructure in the flood prone and non flood prone areas.
The settlers prefer to construct their building in the non flood prone areas in the first stage of the settlement. As the age of the settlement in the non flood prone area is more than the flood prone area, the trails have had more time to upgrade to the local trails. As a result, there is more developed network of local trails in the non flood prone area in the comparison with flood prone area.
As the adjacent collector trail beside the flood prone area was upgraded to the formal infrastructure by the government after in the middle ages of the settlement, some new settlers preferred to construct their building in this area. So, the personal trails have developed more in this area. As the result the fractal dimension of the infrastructure in the flood prone area is a little more than the non flood prone area.

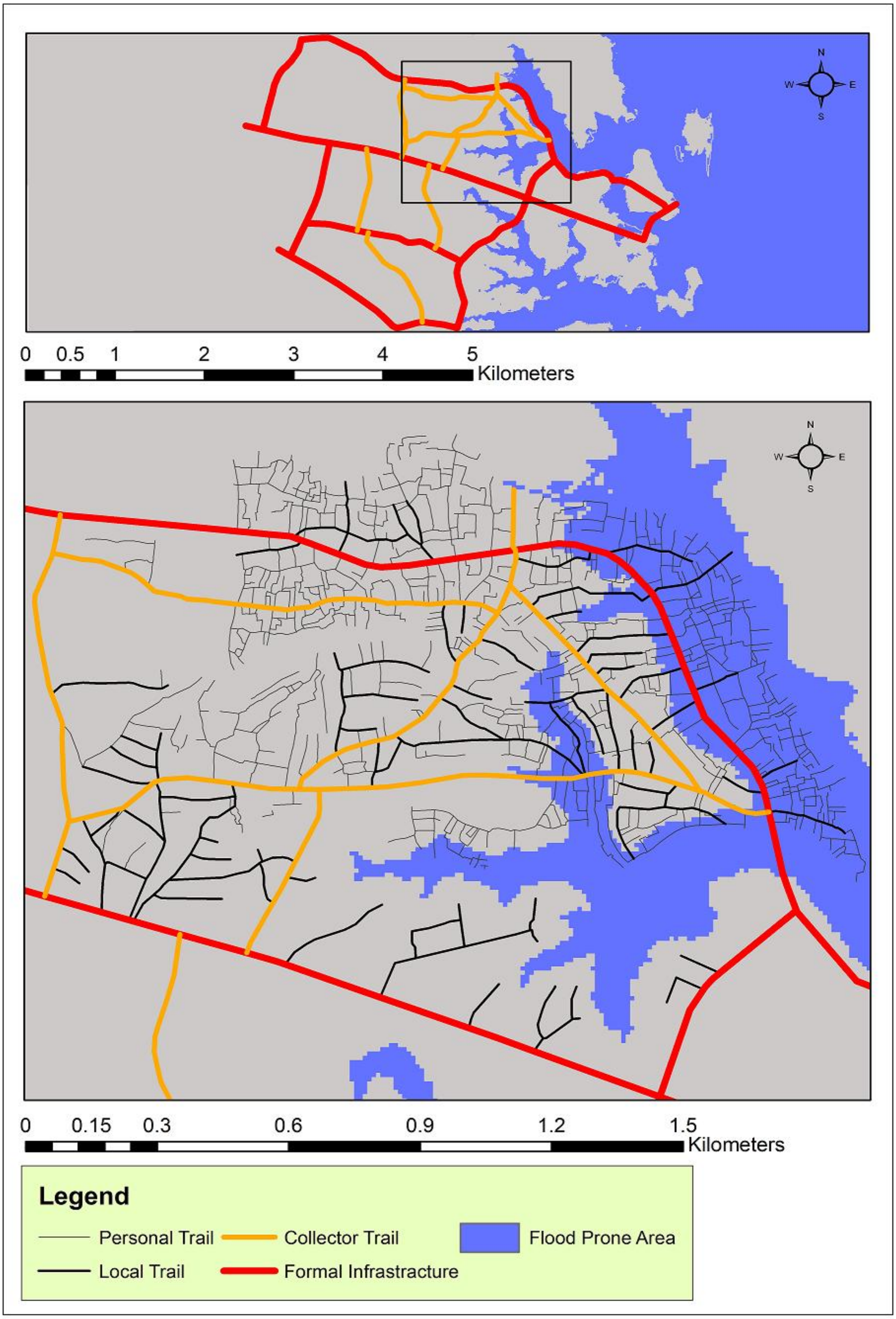


Figure 3.10: Flood prone areas in the study area

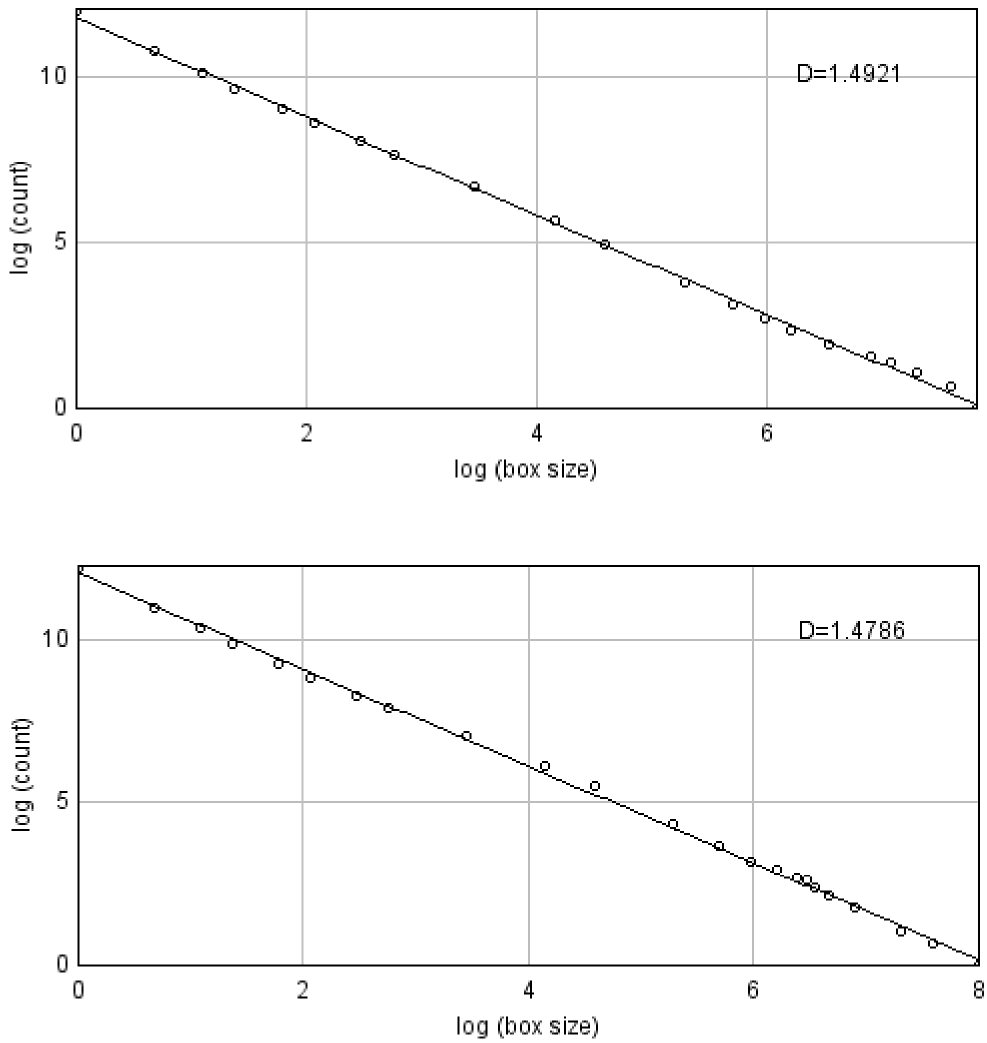


Figure 3.11: The fractal dimension of the infrastructure in the flood prone area (top) and non flood prone area (bottom) based on the box counting method

3.7. Geometric relationships in infrastructure

Roads do not only respond to the environment they run over but are also a system in themselves. They have an organization with certain characteristics and in this section we try to characterize these aspects. The following headlines will be discussed in this section based on some possible regularities in the infrastructure formation:

- Infrastructure structure
- Angles
- Length of infrastructure

3.7.1. Deformed grid structure

Different social, economical and physical factors influence the growth of infrastructure. This applies on the different levels of infrastructure and to the different time periods and zones. These different forces make the infrastructure network as a complex system. So, the definition of the structure of the infrastructure in the informal settlement is a very difficult task.

The infrastructure in the informal settlement was divided in to four categories to differentiate the different structure of different types of infrastructure based on the different formation dynamics of them. Formal infrastructure in the informal settlement can be divided in to two main categories.
The formal infrastructure which was directly built in the top down manner by the governments is categorized in the first category. This type of formal infrastructure which is used mostly by vehicles has a structured and planed form and fully obeys the transportation and urbanism rules.
In the second category, there is formal infrastructure with the bottom up nature of formation. This type of formal infrastructure is the remains of old important trails (which were used by many users) which are upgraded to the formal infrastructure. The form of this type of formal infrastructure was improved and structured (as much as possible) by geometric improvement engineering operation and the other parameters of the infrastructure (such as width, pavement quality) it is rehabilitated.
The collector trail is categorized in the lower category of infrastructures in the informal settlement. They are mostly longer and wider than the lower levels in the hierarchy but not as structured and improved as the formal infrastructure.
It is observable that the collector trails connect to the formal infrastructure and make a deformed grid structure. This deformed grid network divides the zone in to the deformed semi-rectangular-like areas (settlement blocks) (Figure 3.12). This mesh shape structure with semi rectangular grids is formed to ease the collection of the trips from the inside network of local and personal trails.

Figure 3.12: Deformed grid structure which is produced by the formal infrastructure and collector trail network in the analysis study area

The formal infrastructure and collector trail in the analysis study area were divided in to 13 areas. The maximum, minimum and the average area of these 13 areas are 1.52, 0.12 and 0.55 square kilometres respectively. Figure 3.13 shows the frequency distribution of the area of the deformed grids in the formal infrastructure and collector trail network in the analysis study area.

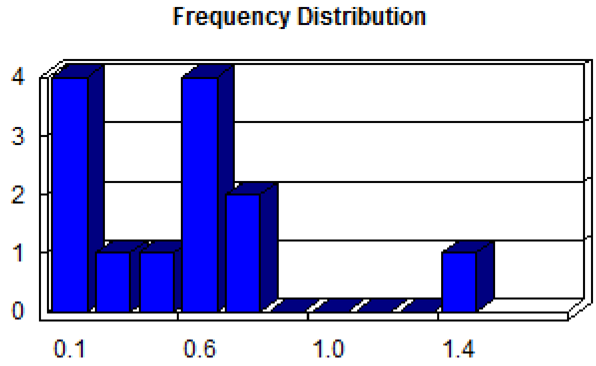


Figure 3.13: The frequency distribution of the areas (km2) of the deformed grids in the formal-collector infrastructure network

3.7.2. Pro-Steiner structure

As was mentioned in chapter 2, Helbing et al.(1997) studied the formation of trails between points (as destinations) and showed that trail formation process moves towards the formation of a minimum detour system. Helbing et al. study indicate that in the formation of trails between four points, the process of the trail formation moves from the minimum way system structure towards the minimal way system structure (Steiner structure). However as the pedestrians prefer to have less detours, the minimal detour system will be formed before the trail's growth reaches to the minimal way system structure (Figure 3.14).

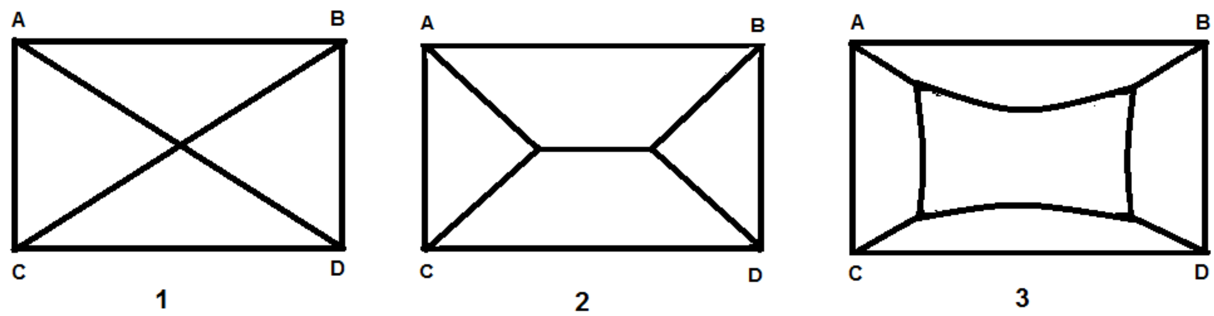


Figure 3.14: The direct way system structure (1), the minimal way system structure (2), the minimal detour system structure (3) between four points

Goldstone et al. (2006) study shows that the trail formation process between points is in the direction of forming minmum Steiner tree structure and they named these diviations "pro-Steiner deviations".
The pro-Steiner structure has a smaller total length than the direct way system structure but more than the minimum Steiner tree structure.
The minimal detour system structure is a kind of pro-Steiner structure that there is a compromise between the characteristics of the minimal way system structure (Steiner tree) and the direct way system. In the other word, the minimal detour system has a shorter total network length than the direct way system (inherent this characteristic from minimal way system structure) but fewer detours from the direct path (inherent this characteristic from the direct way system) in comparison with the minimal way system. In contrast, the local and personal trails usually are built during the development of the settlement to provide the accessibility of building blocks, so the evolution of them will be

stopped quickly by the buildings which will be built beside them. As a result, the emerging of the direct way structures are more popular among these types of infrastructure.

The pro-Steiner like structure can be seen in the areas where the trail formation process had enough time for evolution from the direct way system to minimal detour system. The formal infrastructure with a bottom nature (which are the remains of old trails) and the collector trail which are mostly the first paths built in each area have more chance to have a proper evolution time.

The pro-Steiner like structure is observable in a part of collector trail in the analysis study area.

Figure 3.15 shows a part of the analysis study area. The pro-Steiner like structure connects four points of A, B, C and D. The edges between each two vertices and the diagonals of the ABCD polygon create the direct way system which connects each two points directly and with the shortest length. In Figure 3.16 only the collector trails between four vertices (points) of the ABCD polygon and also the direct ways system between these four points were depicted. The total length of the four edges of the ABCD polygon is 6515.7 meters. Also, the total length of collector trails which connect these four points is 4426.85 meters. So, as it is expected pro-Steiner like structure has less total network length than the direct way system. However as it is obvious the pro-Steiner structure does not achieve to the prefect minimal detour system structure.

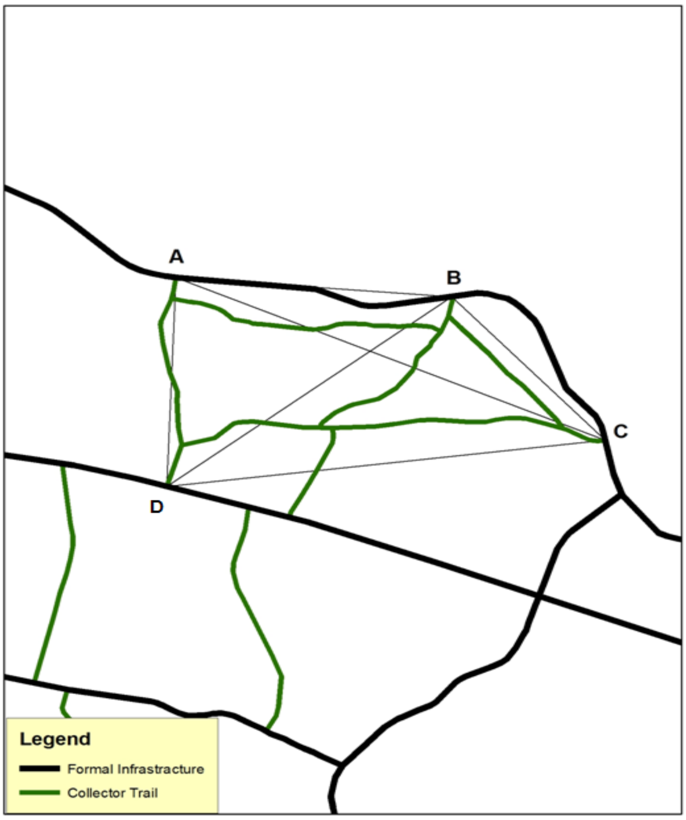


Figure 3.15: The pro-Steiner like structure connects four points in the part of analysis study area. The 4 points create the ABCD polygon. AC and BD are the diagonal of this polygon

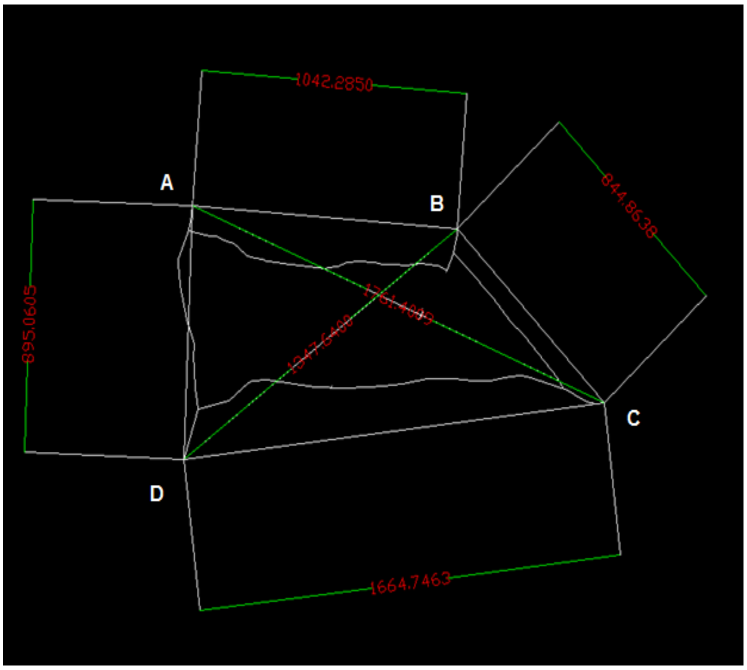


Figure 3.16: The collector trails and the direct way system between the vertices of the ABCD polygon. The length of the edges and the diagonals of ABCD polygon are shown in meter

The studies of Helbing et al. and Goldstone et al. were done without the consideration of the different driving forces (like: slope and obstacles) which influence the formation of trails.

The distortions in the pro-Steiner like structure are possibly because of the different forces (like: avoiding of the trail to pass from the steep slopes and physical obstacles like swamps and pre-built buildings) influence of the formation of the trail in the complex system like informal settlement.

Also as it was discussed before on the results of Goldstone et al. study on the formation of the trail between four points (with rectangular formation), when the size of the rectangle increases the formation of pro-Steiner structure will become harder. This rule can be generalized to other 4 points structures. So, as there is a long distance between the vertices of the ABCD polygon, the pro-Steiner less developed.

3.7.3. Angles

- **Hypothesis:**

The angle of intersection between four types of infrastructure is 90 degree.

- **Approach:**

Calculation of the angles of intersections in the infrastructure network and classification of the results based on the different type of infrastructure which participate in the intersection.

- **Method:**

The vector layer of the infrastructure was exported to the AutoCAD software. The angles of intersections were extracted based on the different types of the infrastructure which participate in the intersection. To achieve this, the minimum intersection angles of the different infrastructures were calculated (Figure 3.17). Rank 1 as the highest infrastructure rank was assigned to the highest level (formal infrastructure) in the infrastructure hierarchy and the rank 4 was assigned to the lowest level (personal trail) in the hierarchy. Ten different intersection cases can be identified based on the different types (ranks) of infrastructure which participate in the intersection, so the intersections were categorized in to the ten classes. The intersection angle of each class member was calculated. Finally, the average value of intersection angle was calculated for each class of intersection.

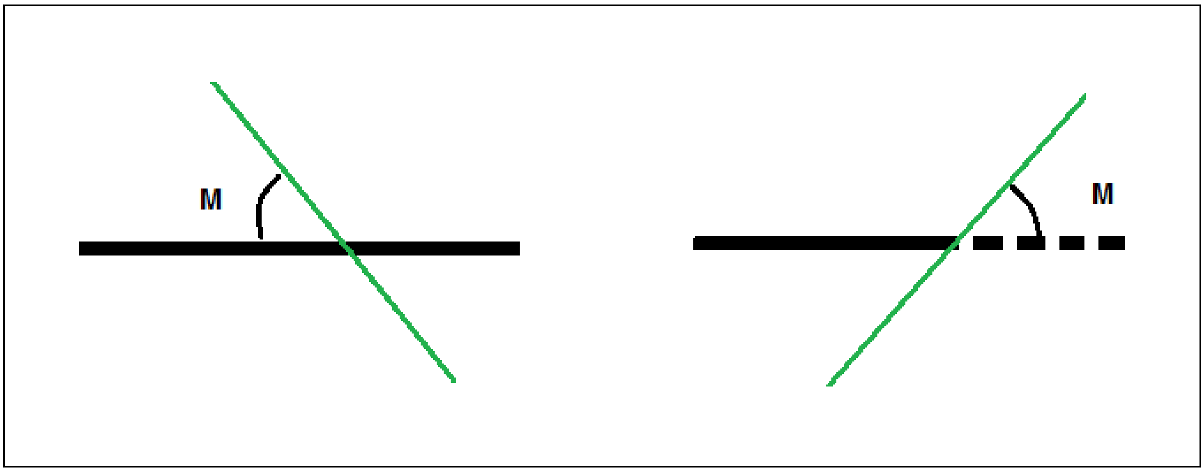


Figure 3.17: The minimum intersection angle of two different types of infrastructure (M)

- **Results:**

The results of the study illustrates in the Table 3.7.
In the cases of two different types of infrastructure (from the rank 1 to 3) that intersect each other, the results shows that the intersections with the higher ranks of infrastructure have more intersection angle value (and nearer to 90 degree) than the intersections with the lower ranks of infrastructure.

For example 88 % of intersection angles in the formal infrastructure - formal infrastructure category have intersection angles between 85 to 90 degree. This value is 58 % for the Collector trail- Collector trail category. Also 57 % for the intersection angles in the Local trail- Local trail category have intersection angles between 80 to 90 degree.
In the cases when there is a infrastructure with a rank 4 in the intersection (cases with the infrastructure ranks: (4-4),(3-4), (2-4) and (1-4)) the average intersection angle increases in the order of the sections with the ranks of (3-4),(2-4), (1-4) and the intersection angle of the type with the infrastructure ranks (4-4) is little more than the type with the infrastructure ranks (1-4).

Type of Infrastructure Intersection	Rank		Average (Degree)
Formal infrastructure - Formal infrastructure	Equal	(1-1)	86.1
Collector trail- Collector trail	Equal	(2-2)	76.2
Local trail- Local trail	Equal	(3-3)	75.6
Personal trail- Personal trail	Equal	(4-4)	83.8
Formal infrastructure - Collector trail	Higher-Lower	(1-2)	85.6
Formal infrastructure - Local trail	Higher-Lower	(1-3)	78.4
Formal infrastructure - Personal trail	Higher-Lower	(1-4)	82.6
Collector trail- Local trail	Higher-Lower	(2-3)	71.5
Collector trail- Personal trail	Higher-Lower	(2-4)	81.8
Local trail- Personal trail	Higher-Lower	(3-4)	80.8

Table 3.7: The average intersection angle per the type of infrastructure intersection

- **Discussion**

The increasing of the intersection angle by the increase of the infrastructure rank in the intersection (In the intersections with the combination of infrastructure ranks of 1 to 3) can be explained by: as the ranks of infrastructure increase in the intersection, the regularity in the form of infrastructure increase. In the other words, as the regularity in forms of the infrastructure increases (and the sharp variations in the forms of the infrastructure decreases) from formal infrastructure to local trail, the possibility of the occurrence of the intersections with nearer angle to 90 degree increases. This trend is the same in the personal trails but the exception is the intersections of the infrastructure with the ranks (4-4). The intersection angle of intersection in this category is little more than the infrastructure with the ranks (1-4). This can be explained in this way that as the personal trails directly connect to the buildings, the network of personal trails have more regular structure which is near to the shape of rectangular building blocks.

3.7.4. Length of infrastructure

- **Hypothesis:**

Highest level of infrastructure (formal infrastructure) has the longest length of segments among the other types of infrastructure and the lowest level of infrastructure (personal trail) has the shortest length of segments in the infrastructure hierarchy.

- **Approach:**

Calculation of the length of the segments in each type of infrastructure.

- **Method:**

The lengths of the segments of four types of infrastructure were calculated and the average length value for each class of infrastructure calculated. Split line segments were merged to ensure that the length of the line was measured as the length between two intersections.

- **Results:**

Table 3.8 illustrates the mean length of infrastructure segments in each type of infrastructure. Figure 3.18 shows the frequency distribution of the length of segments in each infrastructure class.

Type of Infrastructure	Mean of Length (m)
Personal Trail	55.54
Local Trail	146.55
Collector Trail	971.98
Formal Infrastructure	2152.70

Table 3.8: The mean length of infrastructure segments in each type of infrastructure

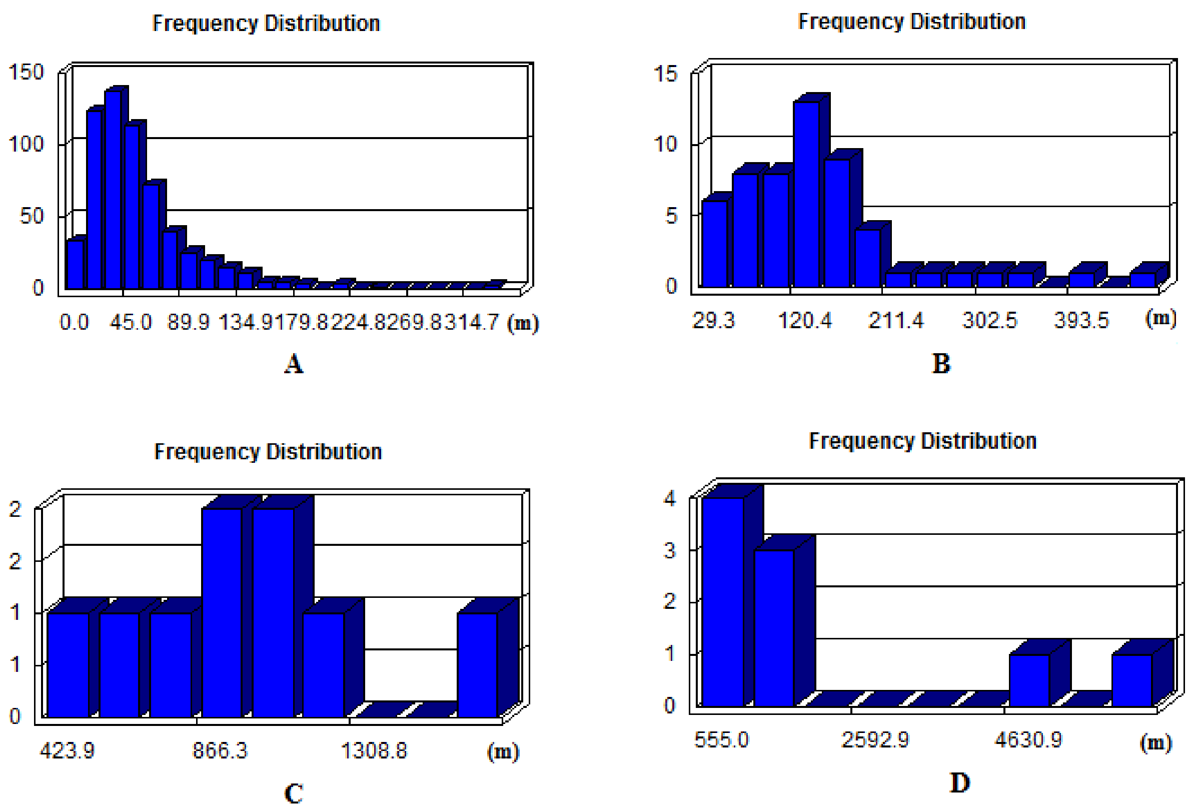


Figure 3.18: The frequency distribution of the length of segments in: personal trail (A), local trail (B), collector trail (C), formal infrastructure (D)

- **Discussion:**

As it is illustrated in the Table 3.8, the mean segment length of each type of infrastructure decreases, as the type of infrastructure changes from the formal infrastructure to the personal trail.

This originates from the different role of each type of infrastructure. As the type of infrastructure decreases to the lowest level (personal trails) in the infrastructure hierarchy, the accessibility role of infrastructure increases. The lowest level of infrastructure concerns with the providing of the accessibly for the buildings.

The network of personal trails conduct the pedestrians trips to the higher levels of infrastructure to take the advantage of increment of the mobility function of higher levels of infrastructure. The length (and the width) of infrastructure increases as the level of infrastructure increases in the hierarchy to provide the better mobility function and collecting the trips of lower infrastructure levels and ease of the travels between the long distance destinations.

3.8. Relationship between building and infrastructure

What comes first the building or the road? One may argue. Does the infrastructure form in between the buildings or do the buildings align themselves to the infrastructure. This type of information is very important when defining a simulation model. The problem with these types of analysis is that the data are lacking. Data were collected with a long temporal resolution, and the process of building houses and development of a road takes much less time. The following section is formulated based on the visual comparison and studying the collected data. Figure 3.19 illustrates settlement growth in a part of the study area from 1967 to 1987. The infrastructure shows the existed infrastructure in 2002. Figure 3.20 shows the informal settlement situation in a part of the study area in 2002.

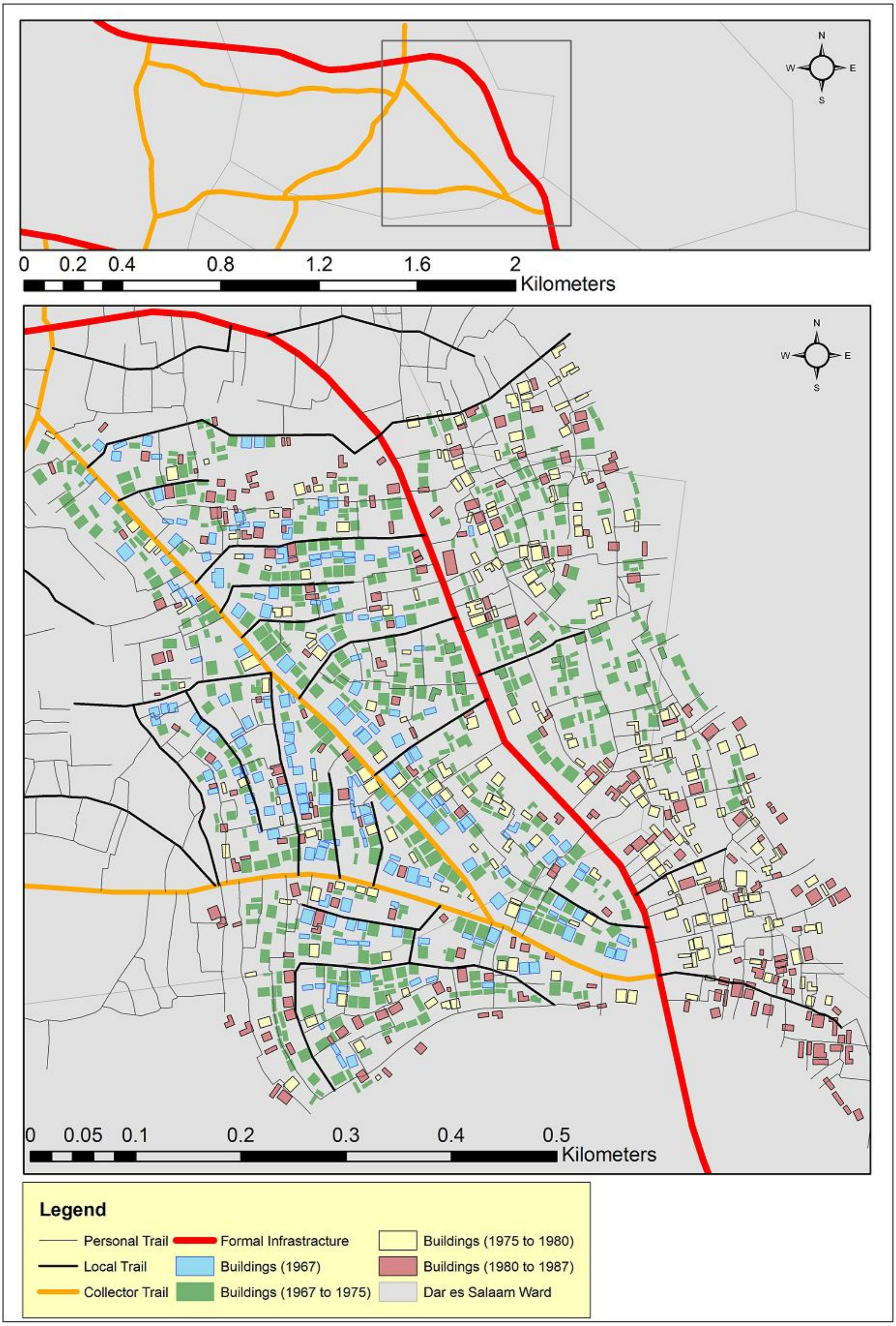


Figure 3.19: The settlement growth in a part of the study area from 1967 to 1987

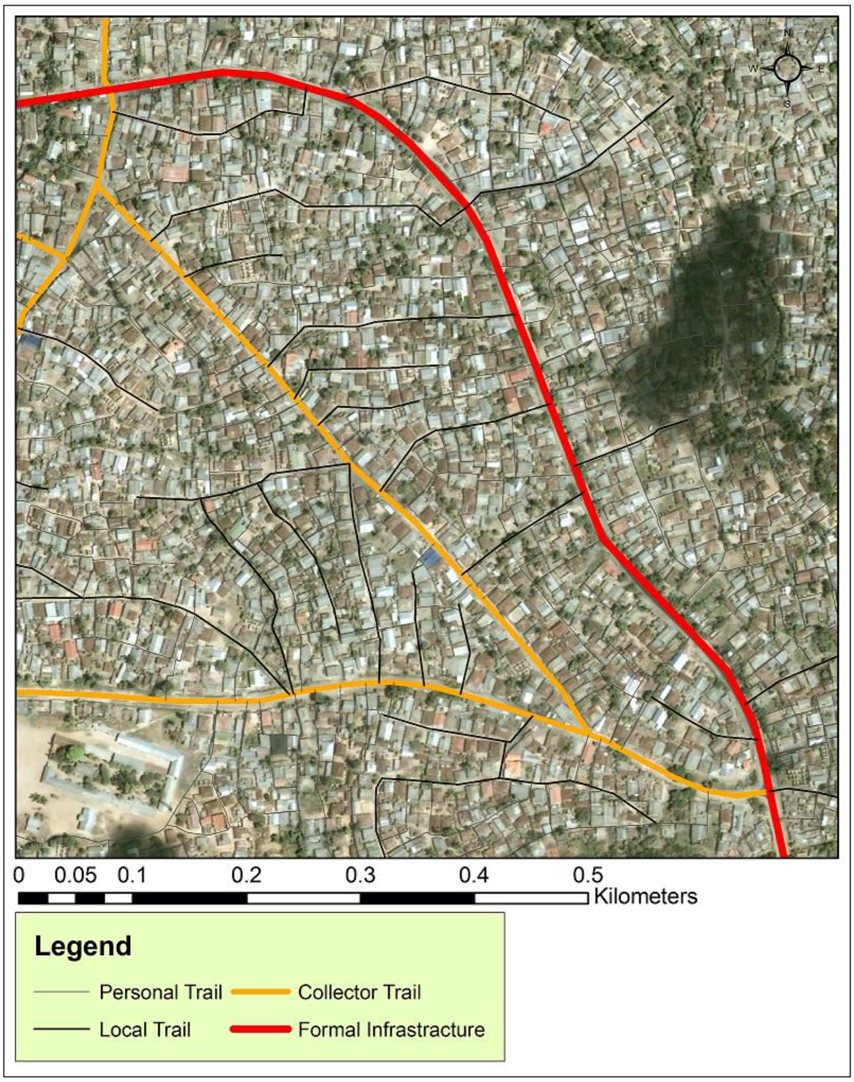


Figure 3.20: The informal settlement in a part of the study area in 2002

3.8.1. Different stages of informal settlement and informal infrastructure growth

The growth stages of informal infrastructure inside the informal settlements can be divided into three main stages.

1. Early stage:

The informal settlement in the area is started in this stage. The settlement is formed in the areas which are near to the formal infrastructures and collector trails (which are pre-existed in the area before the formation of the settlement) and have a better land quality (physical site characteristics).

The buildings which are built adjacent to the formal infrastructure and collector trails are constructed parallel in to these infrastructures.

To provide the accessibly of the other buildings which are not built adjacent to the formal infrastructure and collector trails in the early stage informal settlement, the local trails are formed.

The new buildings are built in the both side of local trails and parallel to them as the informal settlement process is developed in the early stage of the settlement growth.

The local trails are developed and consolidated by the frequent usage of residents during the early stage of the informal settlement.

2. Middle stage:

The infilling and the extension of the settlement in the unbiult lands is happened in this stage.

The unbuilt lands which have a better land quality and more near to formal infrastructure and collector and local trails are selected first and after that the settlement is developed in the other areas (good and lower land quality).

In the case which the buildings may be built in the lower quality lands, some local trails might be formed in the lands which have a better land quality (among the low quality lands). But the main portion of accessibility is provided by personal trails in these areas.

In this that the constructions are extended in the vacant lands which there are no trails to provide the accessibility of residents the personal trails are be formed.

In the period of building construction in the middle stage of informal settlement, the personal trails are developed to provide the accessibly of residents of new buildings to the formal infrastructure and collector trails and also to the local trails in the area. The new buildings are built in the both side of personal trails and parallel to them as the informal settlement process is developed in the middle stage of the settlement growth.

The local trails are developed and consolidated during this stage of the informal settlement. This development is less than the personal trails development because of the shorter time period requirement of personal trails for formation and limited space for their growth (as some buildings are pre-built in some parts of the settlement).

Also, some of the high use previous collector trails can be upgraded to the formal infrastructure in this stage.

3. Final stage:

In the last stage of the informal settlement development, the last available vacant lands (which there is a possibility to construct a building in them) in the settlement are filled by new buildings.

As a number of available vacant lands in the settlement are limited in the final stage of informal settlement, there is a competition between the new settlers to build in the vacant lands.

The final stage of the informal settlement in the settlement has a rapid nature. In this stage of the informal settlement, there is not enough time and vacant space for the formation of new personal trails to provide the accessibility of new buildings.

In the case that the new buildings are built in the areas without any pre-existed infrastructure, the residents use the spaces between each two buildings as a corridor to access to the near structures.

Figure 3.21 shows the parcels (houses) in a part of the study area. The houses can include more than one building. Each parcel has an owner and the unique parcel number (which is depicted on the map). The buildings which are sounded by the infrastructure create the building blocks.

The gray parcels show the buildings which are built near to (parallel to) the infrastructure in one of the buildings blocks. The houses which are placed in the building block (but not adjacent to the infrastructure) are illustrated in brown color. These houses are built in the last stage of the informal settlement growth. The residents of these houses use the spaces between the houses to provide their accessibility to the near infrastructure which are surrounded the building block.

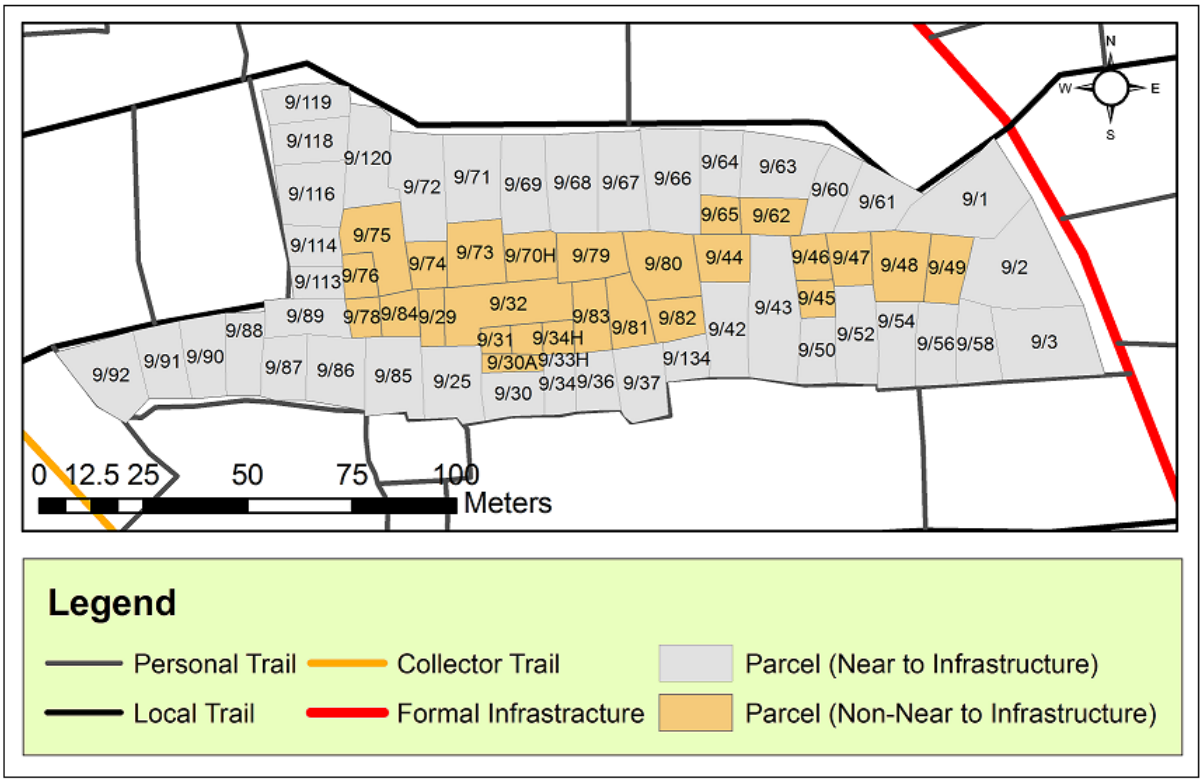


Figure 3.21: The Building blocks in a part of the study area. The gray parcels show the houses which are built near to (parallel to) the infrastructure

4. Conceptual Model

4.1. Introduction

This chapter introduces the conceptual model for simulation of informal growth of infrastructure in the informal settlement Dar es Salaam, Tanzania based on the analysis of the study area in chapter three.
This chapter discusses about the components of the conceptual model. It should be noted that this model is an extension of a housing model for informal settlement of Dar es Salaam, developed by Iqbal (2009). In future this model will be referred to as "the housing model". This chapter will start with a short description of the most important elements of the housing model. In this housing model, the infrastructure is assumed static and without any growth in the period of the simulation.
From the analysis of the infrastructure structure in this area, two different mechanism of infrastructure growth were identified:

- When a new house is built, it needs to connect to existing infrastructure. This lead to the formation of new personal-local trails.
- In a growing settlement, people will have to reach to different locations to perform their daily activities. This can lead to development of collector trails.

To model these two mechanisms, it is required to have a realistic distribution of the settlement's population over the simulated houses. The generation and distribution of the individual's trips from origin to the destination (including the frequency of these trips) is needed to simulate the growth of infrastructure.
The first component of the proposed model (connecting to existing infrastructure) is based on the needs of the residents for connecting their house to the formal infrastructure or collector trails to provide their accessibility to the infrastructure with the higher rank in the infrastructure hierarchy. This part of the model is referred to as the growth of personal-local trails.
The second component (growth of a new collector trail) however has more complex nature. The individual choose the destination where a special activity will be performed by him/her. To reach the destination center which is placed in the relative far distance of the settlement, the collector trail will be formed by the individuals. As the pedestrians like to benefit from the advantages of the existed consolidated paths (as they have a better surface for walking) and high used paths (which caused the pedestrians to feel more safe), the trail can be deviated to the consolidated and high used adjacent path (with the same destination to the destination center) in the process of the collector formation. The collector trail growth model is developed to model the process of the trail deviation in the collector trail formation process (Figure 4.1).
It may be noted that besides the growth processes as mentioned above there is also the development of formal infrastructure by (local) government. This is not included in this model.

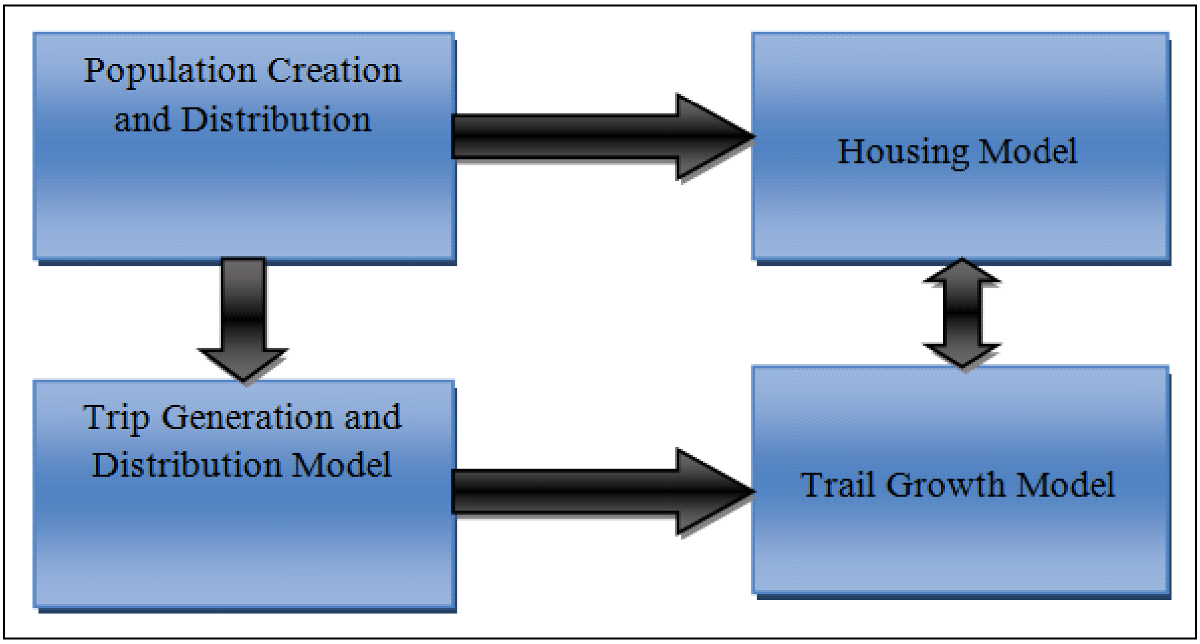


Figure 4.1: The elements of the informal infrastructure growth model

4.2. Housing model

An agent based approach was developed by Iqbal (2009) to simulate the growth of informal settlement in Dar es Salaam. This large scale vector based model considers the dynamics of informal settlement based on the geometrical change in the shape of the buildings.

The proposed model includes different types of people (rich, poor, owner and tenant) who their behaviors are based on their different economic status and also social and environmental factors.

The agents in Iqbal's model can construct a house, extend an existing house or rent a house based on their different behaviors of them (Figure 4.2).

In this model, if the distance of the vacant space to the road and footpath comparably the same, the agents prefer to construct their houses near to the roads compare to the footpath. The agents have an avoidance behavior in relation to the flood risk zones.

As any model, this model has some limitations. The main limitations of Iqbal's model are listed as following:

- Not all social, economical and environmental factors were considered.
- There is no mechanism of buying and selling houses.
- The model assumed that the infrastructure is existed in the study area.

As the proposed model assumed that the social and economical situation of the study area is stable and the infrastructure is existed (and without any growth process) during the period of the simulation, this model. This model needs to be modified to consider the dynamic nature of the infrastructure growth in the development of the informal settlement. To approach this goal, the models for modelling of the infrastructure growth will be proposed in the next sections.

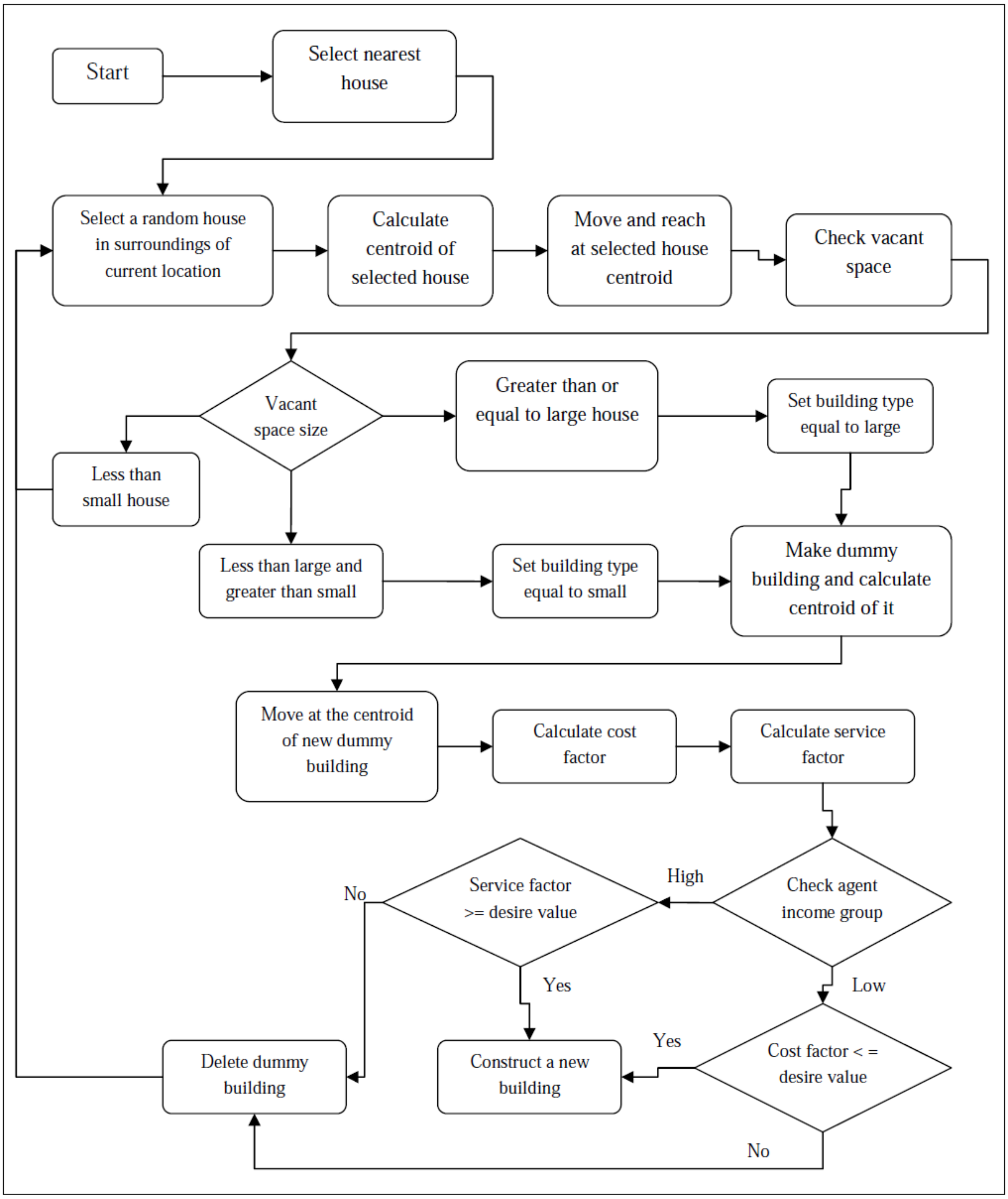


Figure 4.2: Overview of owner agent behaviours in the housing model (Iqbal, 2009)

4.3. Population creation and distribution

The population includes the individuals who live in the houses of the settlement. The resident population in the settlement pursue their daily activities, inside and outside the settlement.

The individual has a number of associated attributes. These attributes can be divided into two categories of static attributes and dynamic attributes. The static attributes of an individual consist of those attributes which do not change during the simulation period. For example the attribute such as gender of an individual has a static characteristic. The dynamic attributes of an individual include the attributes of the individual (like: age of individual) which change over time. However, some of the dynamic attributes can be assumed as static attributes as there they don't have significant changes and effective influence on the simulation process during the simulation period. This is depending on the nature of the simulated problem and the purpose of the model.

The building block of the simulation model is an agent. The agent is the representative of an individual in the reality. In this model, every agent is a member of a specific household. The households are settled in the houses of the settlement.

As the household (includes of the head of the household and the family member) is generated in the system, the household head construct a house or rent a house based on the settlement rules of the settlement model (house construction model). The household population is assigned to the constructed house. The household agents have attributes of: gender, age, worker/non worker, economical status (which is the same for all members of the household) and house location.

As the process of the path formation in the informal settlement has a rapid nature, the attributes of the agents can be considered as static attributes. Also, it can be assumed that as a household population is assigned to the house, the household population is constant and no new birth and death do not happen during the simulation period.

4.4. Trip generation and distribution model

The individual (household member) performing different daily and weekly activities based on the different attributes and lifestyle of himself/herself. The individual usually requires travelling to the activity areas (destinations) for performing specific activity. Some of the individual's activities are done in a repeatedly manner (like going to the working place in the working days) while others individual's activity can be done with a longer time frequency (like going to the clinic for medical issues once a month). In the context of the activity based travel demand modelling, every individual is a decision maker who is faced with various possible choices (activity areas) for performance of his/her daily and weekly activities in the time and space domain.

Iinternal and external factors influence the choice of the individual. The internal factors reflects the characteristics and different attributes of the individual (such as gender, age, worker/non worker, economical status and living location), which influence on the decision making process of the individual. The external factors include the other effective environmental factors (like the weather condition) which are forced on the choice process of the individual.

The individual try to optimize his/her choice and select the best activity area to satisfy his/her goals and perform the activity with minimum physical activity and in the least possible travelling distance and time.

It is assumed that the individuals with similar attributes (economical status, gender and age range) in the same settlement have the same travel activity pattern. Figure 4.3 illustrates the different individual types in the model. For example all of the individuals who are poor, male and from a specific age range have a same travel activity pattern. This type of an individual needs to supply the drinking water from the water pump for his family while the other rich male individual from the same age range do not do this activity.

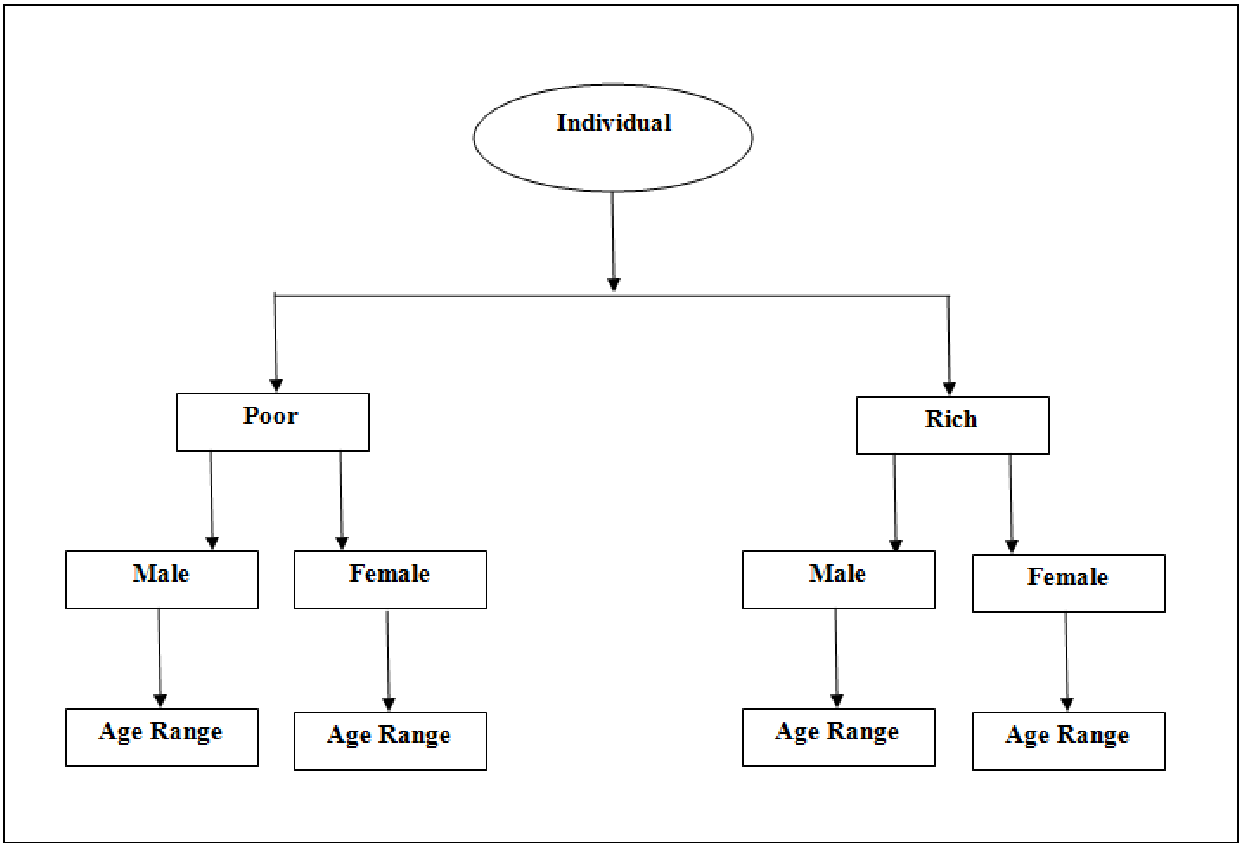


Figure 4.3: The different individual types in the model

The travel demand model produces a daily travel activity table per an individual based on the individual type. In this table the activity (or activities) of the individual is defined per each day and the location of the activity area is mentioned per an activity. The output of this table indicates the travelling pattern and decisions of the different types of the individuals in the disaggregated format.

4.5. Informal trail growth models

In the following sections two models will be proposed for the informal growth of personal, local and collector trails as the main aim of this chapter. In the first part, the model environment is introduced for the both model. In the following sections, two different proposed models will be discussed.

4.6. Model environment

Each agent based model has two main components, agent and environment.
The environment provides the space (landscape) for the agents to act in it and having an interaction with the other agents and the environment.
The proposed models contain the following environments:

- An environment which contains the infrastructure (the formal infrastructure, collector trails, local trails and personal trails).
- An environment which contains houses.

4.6.1. Infrastructure environment

The infrastructure environment is formed from the grid structure. The links in the grid structure represent the possible trail segments between each two adjacent nodes (Figure 4.4).

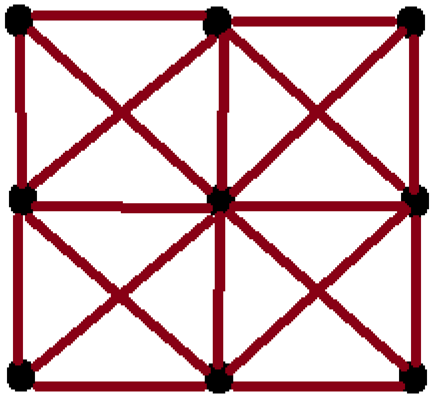


Figure 4.4: Infrastructure environment

The infrastructure consists of the formal infrastructure, collector trails, local trails and personal trails which represent as poly-line in the environment.

Every poly-line has six fields in its attribute table. For each link in this layer, the attribute table's field named "Link_ID" records the link's specific number. Each poly-line has two another fields in the attribute table named "FromXY" ,"ToXY" which record the coordinates of starting and ending of each poly-line (coordinates of the grid nodes). The field named "Existance" in the attribute table as a Boolean value records if the link is used as an infrastructure segment or not.

As each link can represent one of four types of infrastructure (formal infrastructure, collector trails, local trails or personal trails), the attribute's field "InfraType" defines the type of infrastructure.

The fields "UserCount" and "HouseCount" record the number of agents who use from each link (as an infrastructure segment) and the number of the different houses which use from each link (as an infrastructure segment). Also the "Impedance" field in the attribute table records the cost of passing from the link (as a possible infrastructure segment).

4.6.1.1. Slope Impedance

Slope is one of the main components of the landscape. The slope values are classified in to three categories.

The slope degrees which are equal or less than the suitable range of trail's slope degree are classified in the suitable range of slope category.

The slope degrees which are greater than the suitable range of the slope degree but less than or equal to the maximum acceptable slope degree of the trail are categorized in the second category.

The third category contains all of the slope degrees greater than the maximum acceptable slope degree. The agent considers these three categories when it wants to construct a trail.

The agent prefers to construct the trail in the areas which are placed in the first category of slope range in comparison with the areas which are placed in the second category of slope range. The agent avoids constructing the trail in the areas which are located in the third slope range category. The links in the infrastructure environment which are placed in the first category of the slope degree have the least impedance and the links which are placed in the last category of the slope degree have the highest impedance (as the agent avoid to pass from these areas) in the respective field in the attribute table. The links in the infrastructure environment which are placed in the second category of the slope degree have the higher impedance than the links which are placed in the first category of the slope degree.

4.6.1.2. River Impedance

The river has a role of physical obstacle and the trail cannot pass from the river. The agent considers the river as very high cost area during the calculation of the cost value for the formation of the personal and local trails. So, the links in the infrastructure environment which have an intersection with river (as polyline) have very high impedance in the respective field in the attribute table

4.6.1.3. Swamp Impedance

The infrastructure cannot construct in the swampy areas. So these areas are considered as very high cost areas for the agents when in the calculation process of the cost value. The links in the infrastructure environment which have an intersection with swamp (as polygon) have very high impedance in the respective field in the attribute table

4.6.2. Building environment

The building environment contains houses (the residential buildings) and non residential buildings which were built in the study area. The buildings as polygons work as physical obstacles, so the infrastructure cannot pass from the houses.
There are two main types of houses in Dar es Salaam. The houses which contain of a single building and the houses which consist of two or more buildings.
In the case that the house consist of two or more buildings, the space between the house's buildings is considered as house property and the infrastructure cannot pass from it.
The building environment has a dynamic nature. As a house is created by the housing model, it will be added to the house environment. Whenever a new house (or a non residential building) is added to the environment, the link(s) in the infrastructure environment which have an intersection with the new house polygon (or non residential building) will get very high impedance value (as the building is considered as a physical obstacle, so the trail cannot pass from it).

4.7. The informal trail growth model for providing of the initial houses accessibility

The informal growth of the personal and local trail has the similar dynamics based on the results of the different analysis in the chapter three. The main portion of the personal and local trails has been developed by the residents of the settlement to provide the initial accessibility of the houses to the higher infrastructure levels.
This model is based on the influence of the environmental, physical, social and economical components of the city.
Like every model, the proposed model simulates some part of the reality based on some assumptions.
The assumptions in the proposed model are as following:

- The settlement is formed near to the pre-existed formal infrastructure and collector trails.
- There is no preference between the formal infrastructure and collector trails for an agent for connection of the personal and local trail to them.
- The trail is formed by the human and the vehicles do not have any role in this process.
- The settlement model which generates the buildings considers the factor that the residents prefer to construct their houses along the infrastructure.
- The model does not consider the human's random deviations from the perfect least cost path (from each house to the formal infrastructure or collector trail) in the process of trail formation.

4.7.1. Principles of the model

Naturally, pedestrians like to minimize their metabolic energy expenditure during walking between destinations in the natural environment. The pedestrians prefer to reach to their destinations with the least possible distance and time. To approach these goals, the pedestrians endeavour to avoid passing from the steep slopes and physical obstacles and they try to minimize the travelling distance between their destinations.

In the process of the personal and local trail formation for providing of the initial houses accessibility, the trail segment is formed directly after the construction of each house to provide the accessibility of the house to the higher level of infrastructure (formal trail and collector trail). The residents consider the steep slopes and physical obstacles as a negative parameter and the minimizing the path length (from the house to the destination) as a positive parameter in the trail formation process. They also tend to take the advantage of existed trails to reach the higher level of infrastructure. As the existed trails are used by the other residents they are more consolidated and crowded which they reduce the energy consumption by the pedestrians and satisfy the human social interests by crossing from the more used paths.

In the process of the trail formation, it is possible that the new houses are constructed in the direction of unconsolidated (preliminary) paths. In this case, the individual who his/her used path is blocked will change his/her path to reach to the formal infrastructure and collector trail by the new minimum cost path. When a trail is consolidated, no building will be built on the path of the trail by the residents based on the settlement's social contracts.

4.7.2. General procedure of the model

The general procedure of the model for the simulation of the growth of personal and local trail (which provide the initial houses accessibility) is as following (Figure 4.5):

1. The agent will check if this building is within a certain Euclidean distance of existing infrastructure if not:
2. The cost of the minimum cost path and the less than the minimum cost possible path to the existed formal infrastructure or collector trail are calculated over the infrastructure environment based on the links impedance values.
3. The costs of the paths are ranked from the lowest cost to the highest cost.
4. A decision mechanism will compare and select the suitable path or paths.
5. The path segments which are selected by each agent are marked by an agent per each agent's passage.
6. If the number of agents which use from each path segment is exceeded more than a defined value, the segment will be converted to a line segment (as a track of personal trail) and added to the current infrastructure.
7. The previous process will continue for each house in the period of the simulation until the house is connected to the infrastructure network which provides the accessibility of the house to the formal infrastructure or collector trail.
8. If the number of the houses which use of each path segment is exceeded more than a defined value, the personal trail will be upgraded to the local trail.

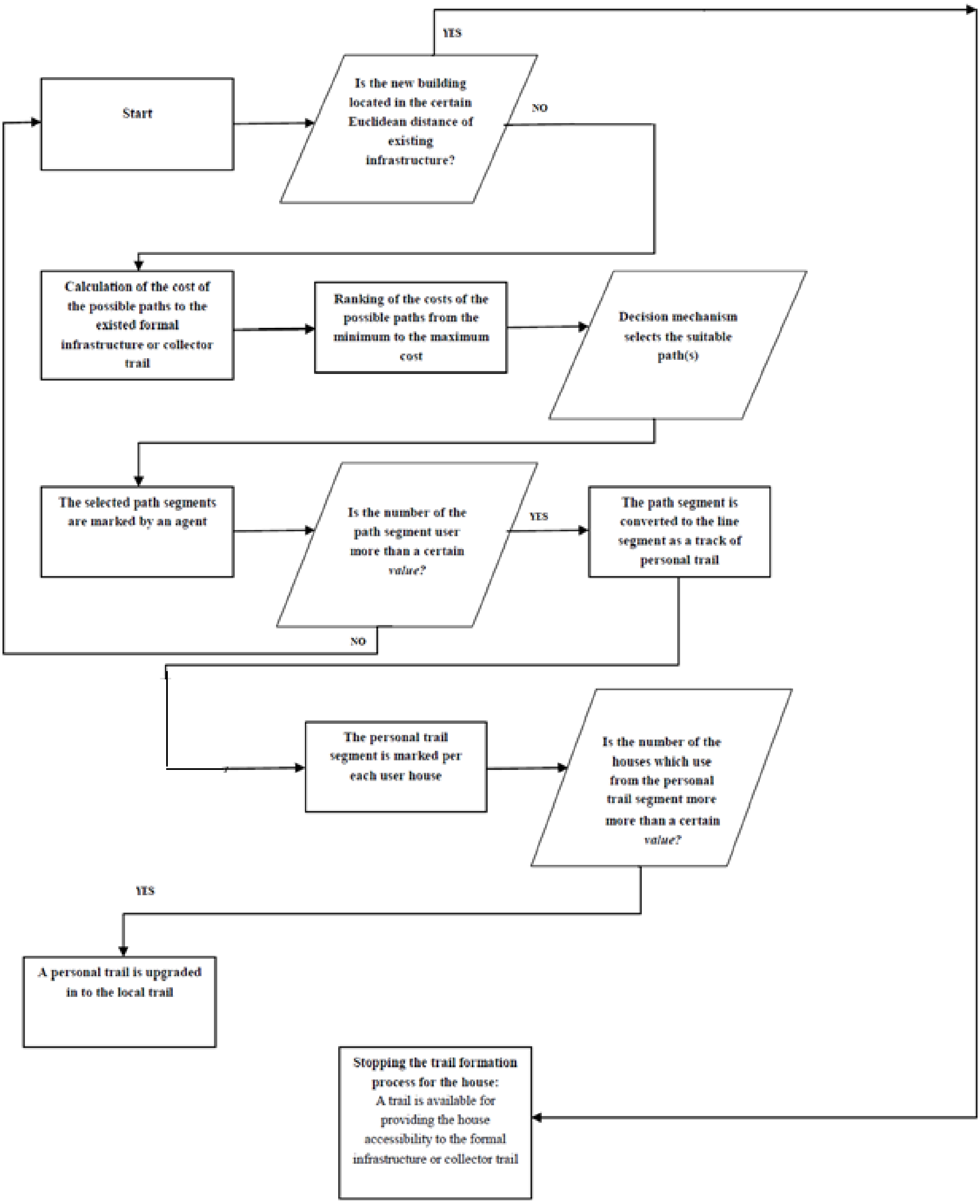


Figure 4.5: Procedure of the personal and local growth model

4.8. Model agent

The household members who want to reach to the formal infrastructure or collector trails for reaching to the outside of the settlement (for performing an activity) are the agents of the model. The agents have different economical status, gender and age. They choose the different destinations based on their activity plan.

4.9. Agent's behavior

4.9.1. Checking the house distance to the existed infrastructure

When a building is built in the area the agent will check if there is an existed infrastructure in the nearby of the building. If there is an existed infrastructure in the certain Euclidean distance of the building, the agent use from the existed infrastructure to provide its accessibility to the formal infrastructure and collector trail. If there is no infrastructure in the certain Euclidean distance of the building, the agent determines to construct a trail to provide its accessibility the existing infrastructure in the area.

4.9.2. Finding the closest node in the infrastructure environment to the house

The agent finds the closest node of the infrastructure environment (grid structure). From closest node, the agent will find the possible paths to the closest nodes (from infrastructure grid structure) to the formal infrastructure or collector trail.

4.9.3. Finding the least cost path from nearest node to the house to the existed infrastructure

If there is no infrastructure existed in the certain Euclidean distance of the building, the agent tries to construct a new trail to connect the house to existing infrastructure in the area. The agent prefers to take an advantage of the existed trails as much as possible to reach to the formal infrastructure or collector trail. The agent cannot pass from the physical barriers like river and swamp and pre-built houses in the landscape as they are considered the high cost areas for him/her. The agent prefers to pass from the areas which are placed in the suitable range of slope degree. And it avoids passing from the areas which the slope of them are more than acceptable range of slope degree.

4.10. General model rules

4.10.1. Calculation of the link's (trail segment) impedance

The link (trail segment) impedance (cost) for the respective three categories of the slope degree is calculated for every arbitrary link like the link AB as following (Figure 4.6):

$Im_n = 0.5 * (C_A * d_1 + C_B * d_2)$

Where:

Im_n: Impedance (Cost) of passing from the link AB which is not used as an infrastructure segment (non-existed infrastructure).

C_A and C_B: Cost of the cell of A and B in the slope cost raster (based on the three categories of the slope degree). These costs are assigned to the nodes of A and B which are placed in the cost cells of A and B in the cost layer respectively.

d_1 and **d_2:** The length of the elements of the link AB which are placed in the cost raster cells of A and B respectively.

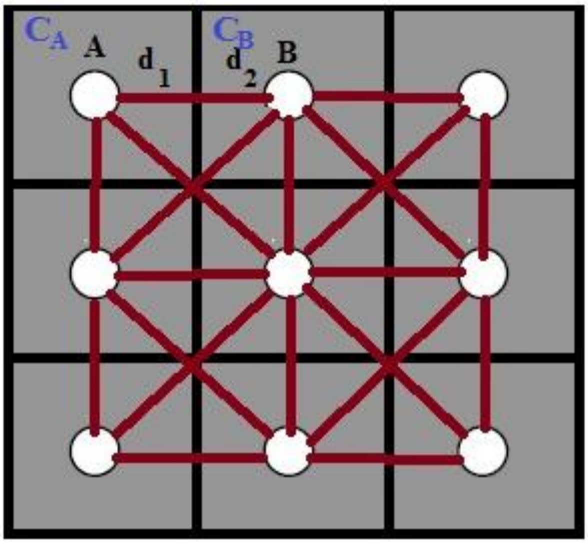


Figure 4.6: Grid structure of infrastructure and the slope cost raster

4.10.2. Correction of the existed trail segment impedance

The associated impedance (cost) value of the grid's link which is used as an infrastructure segment (existed infrastructure) between two adjacent nodes is corrected as below:

$Im_e = W * Im_n$

Where:

Im_e: Impedance (Cost) of passing from the link which is used as an infrastructure segment (existed infrastructure).

Im_n: Impedance (Cost) of passing from the link which is not used as an infrastructure segment (non-existed infrastructure).

W: Cost reduction coefficient, because of the suitability of using the existed personal and local trail network (for an agent) to reach to the closest formal infrastructure or collector trail ($0<W<1$). The suitable value for W can be find by the calibration of the model according to comparision of the simulation results (with the arbitrary W value) with the empirical data.

4.10.3. The decision mechanism:

If all of the total cost values of forming the possible paths are the same, the possible paths are selected by the decision mechanism. If not:

The total cost value of the first path with the lowest cost is compared to the less than the minimum cost possible path. In this case:

If:

$Cost_1 \ll Cost_2$ **:** The first lowest cost path in the ranking (the least cost path) is selected.

If:

$Cost_1 \leq Cost_2$ **:** The least cost path and the less than the minimum cost possible path are selected.

Where:

$Cost_1$: The cost value of the first lowest cost path in the path cost ranking.

$Cost_2$: The cost value of the path number 2 in the path cost ranking.

4.11. The informal trail growth model for formation of the trails to/between the centers

In this section, a model is proposed for the trail formation to or between the centers.
In the following two main types of the center are defined: service center and virtual center.
The simplest form of the center is the service center (like: School, clinic, water pump). These non residential buildings provide the different services for the residents (Figure 4.7).

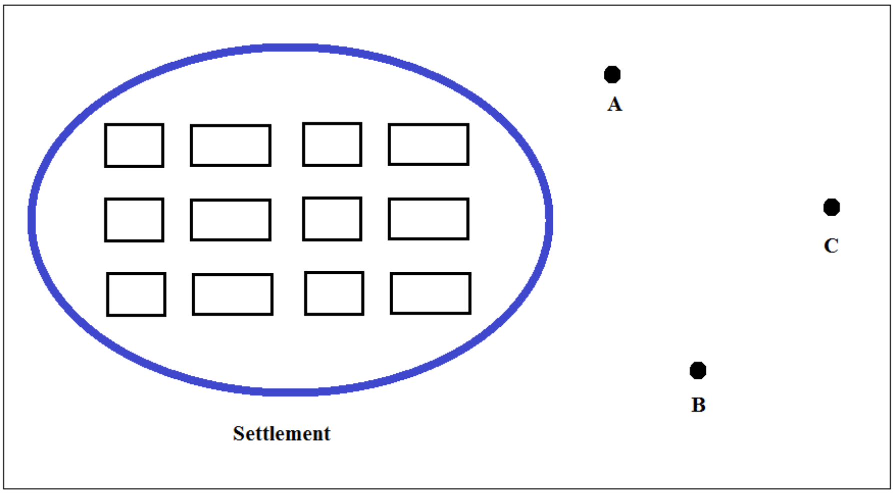


Figure 4.7: The centers A,B and C represent the service centers which provide the different services to the settlement

The virtual center is the structure which can be assumed as a center in the specific cases. In the following, some of the structures which can be assumed as a center in the context of the informal settlement are listed:

- A building complex which contains number of buildings (such as a settlement, economical complex etc.) can be assumed as a center when the process of the trail formation is studied from a center to the building complex which is placed in the far relative distance. Figure 4.8 illustrates two settlements which are placed in the far distance from each other. In this example, two settlements can be assumed as centers in the simulation of trail formation between two settlements.
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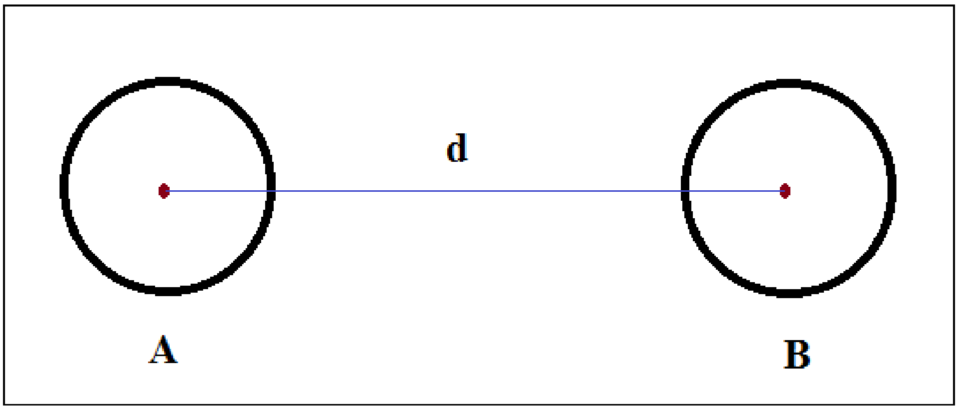


Figure 4.8: The settlement A and B can be assumed as the centers as the relative distance between them is long

- The end point of the existed formal infrastructure and collector trail can be assumed as can be assumed as a center when the end point is placed in the far relative distance from the settlement. In this case the residents of the informal settlement may form a trail to the end point of the existed formal and collector infrastructure and develop it to beneficiate from the connection to the existed infrastructure.

Local trails and collector trails can be formed by this dynamic according the amount of the distance between the settlements to the center. In the case that the center is placed in the relative near distance from the settlement the local trail is formed. In the case that there is a long relative distance from the point to the center the collector trail can be formed.
This model is based on the influence of the environmental, physical, social and economical components of the city.
The proposed model simulates some part of the reality based on some assumptions. The assumptions in the presented model are listed as following:

- The trail is formed by the human and the vehicles do not have any role in this process.
- The model does not consider the physical obstacles in the pedestrian deviation process from the path.
- The model does not consider the housing process beside the trail which prevents from the gradual deviation in the trails path.
- The model does not consider the human's random deviations from the perfect least cost path (from each house to the formal infrastructure or collector trail) in the process of trail formation.
- The center is not accessible by the formal infrastructure and local trail.

4.11.1. Principles of the model

In the process of the trail formation to/between the centers, first the pedestrian try to reach to the destination center with least distance and time. Also the pedestrians endeavour to avoid passing from the steep slopes and physical obstacles as they seems the negative factors in his/her walking process.
The pedestrian naturally prefers to pass from the consolidated paths. The consolidated paths are used frequently by the other pedestrians so the surfaces of them are more suitable for working. Also as many pedestrians pass from the consolidated paths, the pedestrian feel more safe.
During the formation of a new the trail to the destination center, if there is the other consolidated trail in the nearby with the same destination, the pedestrian try to deviate his/her path to the nearby trail. This process is formed during the time to benefit the pedestrian from the advantages of the consolidate path.
As it was mentioned in the chapter two, Helbing et al.(1997) and Goldstone et al. (2006) study show that if the this process have enough time to develop, finally causes that the pedestrian merge some part of his path to the consolidate path to use the advantages of the consolidated path.

4.11.2. Path deviation mechanism

Figure 4.9 (left) shows a pedestrian who walks in the direction of the center C. The pedestrian has an angular field of view from the environment equal to 2α. The Figure 4.9 (right) illustrates a pedestrian who placed at the point M and walking in the direction of B to C. The pedestrian can see the adjacent path (AC) with the angle of equal to α. In the other word the pedestrian who placed at the point M can see the segment NC from the adjacent path (AC).
The first observable point from the path AC (in the direction of A to C) which can be seen by the pedestrian is the point N.

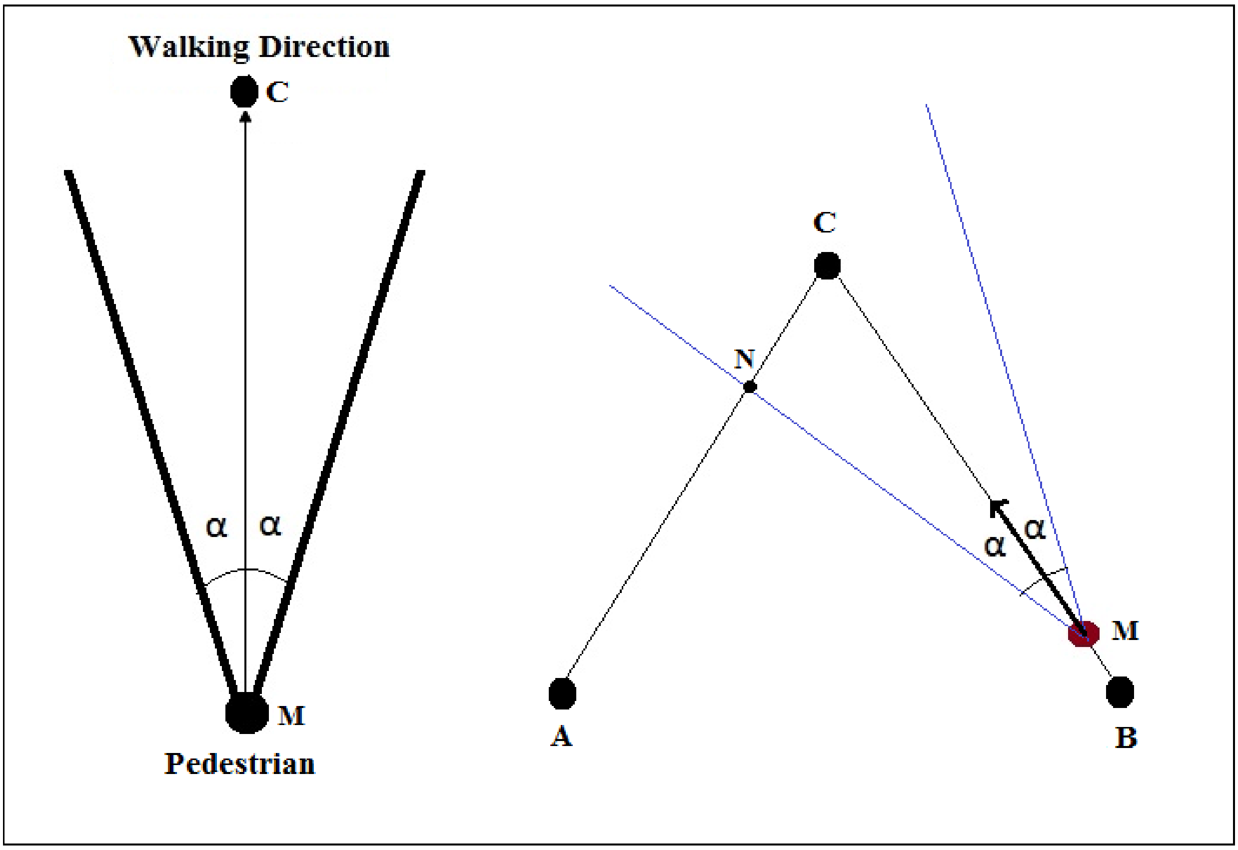


Figure 4.9: The angular field of view (2α) for the pedestrian who walks in the direction of MC (left). Angular field of view for the pedestrian who walks in the direction of B to C (right)

As the center C is the destination of the pedestrian (the main goal of the pedestrian is to reach to the center C), the center C attracts him/her in each instant towards itself.
Also the path AC can attract the pedestrian if it is consolidated and used by many pedestrians. This attractiveness of the path AC for the pedestrian is because of the ease of walking on the consolidated path and feeling of more safety by the pedestrians in the high used paths.
These attractions can be assumed as the external forces which exerted to the pedestrian.
The Figure 4.10 shows the direction of the applied attraction forces from the center C and the path AC in the same time with an exaggeration in the schematic form. As the main goal of the pedestrian is to reach to the center C, the amount of the force which is exerted to the pedestrian by the center C is always more than the path attraction force. The resultant vector of these forces is in the direction of the vector V.
The pedestrian deviates from the path BC if the applied attraction force from the path AC is considerable on him. This force has a direct relation with the quality of the path (paved or unpaved and the amount of the consolidation) AC surface and the number of path AC users. The attraction force from the path AC on the pedestrian reduces or disappears if there is a physical obstacle between the path and the pedestrian (This is because of the fact that the pedestrian avoids to pass from the physical constraints. Also sometimes the physical obstacles prevent the pedestrian to have a vision on the road).
Also the applied attraction force (from the path AC) has an indirect relation with the distance of the pedestrian to the point N on the path AC (the MN length).

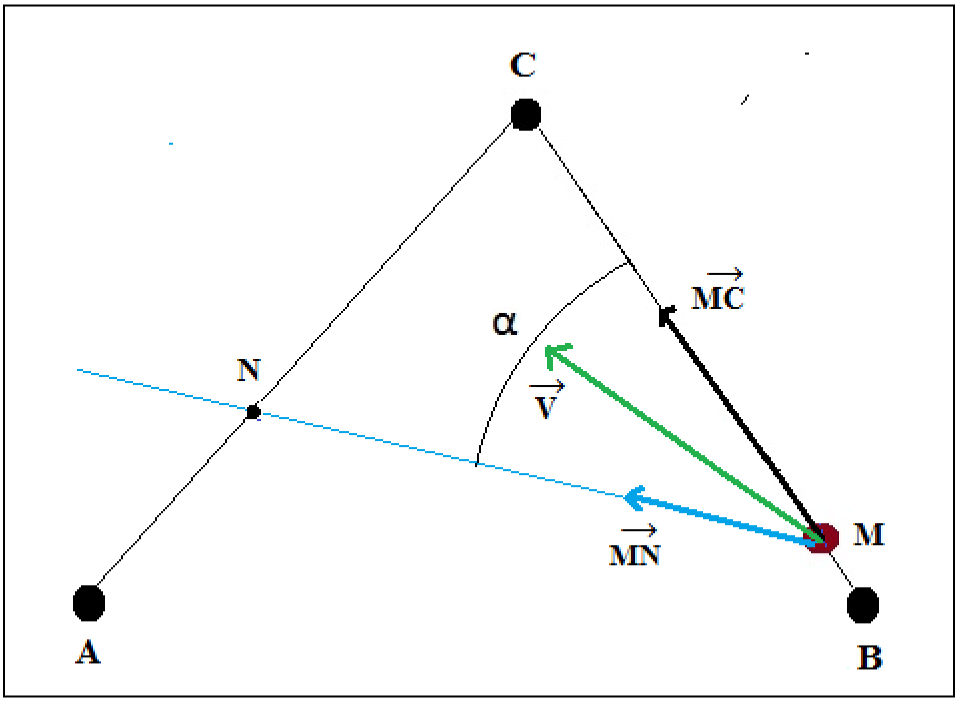


Figure 4.10: The direction of the applied attraction forces from the center C and the path AC to the pedestrian

These relationships can be formulated as following:

$$F_a \propto \frac{A(Q,N,O)}{F(d)}$$

Where:

F_a: The total attraction force which is exerted from the path AC to the pedestrian.

A (Q, N, O): The amount of the attraction force from the path AC because of the parameters of surface quality of the path (Q), number of the path users (N) and the indirect influence of the existence of the physical obstacles in the direction of MN (O).

F (d): The distance function which is directly proportional to the distance between the pedestrian and the point N on the path AC.

The elements of above mentioned formula and the suitable form of the equation can be find by the analysis of the empirical data and also calibration of the model according to comparison of the simulation results with the empirical data.

When the total attraction force which is exerted from the path AC to the pedestrian is exceeded more than a specific value, it can change the direction of pedestrian walking. In this case, the direction of the pedestrian walking is in the direction of the resultant vector ($\vec{V}$) of the F_a force and the exerted attraction force from the centre C on the pedestrian.

The total attraction force from the path AC and the attraction force from the center C are exerted to the pedestrian permanently. Figure 4.11 illustrates the pedestrian who is deviated from the path MC and placed at the point M_1 with an exaggeration in the schematic form. The vector D is the walking direction of the pedestrian when he/she reaches to the point M_1. The total attraction force from the path AC is exerted to the pedestrian in the direction of the vector M_1N_1. A force from the center C is applied to the pedestrian in the direction of the vector M_1C. The pedestrian will change his walking

direction to the direction of $\vec{V}$ which is the direction of the resultant of the attraction force from the path AC and the center C (which is exerted to the pedestrian).
The curve MS in the Figure 4.11 shows the schematic illustration of the deviated the pedestrian path from the path BC to the path AC.

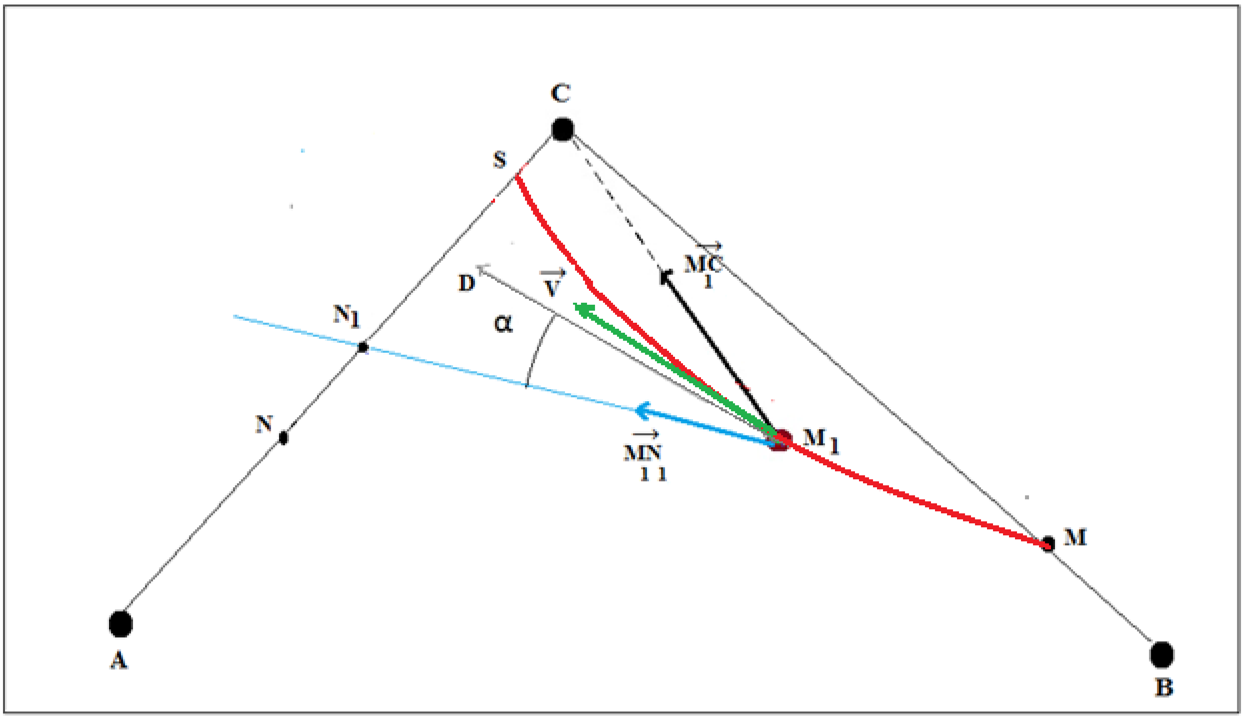


Figure 4.11: The pedestrian deviation path from the path BC to the path AC process

The proposed concept can be generalised to the case which both of the paths applied the attraction force on each other. In this case the pro- Steiner formations can emerge.

4.11.3. General procedure of the model

The general procedure of the model for the simulation of the trail formation from the settlement to destination center is as following:

1. The minimum cost path from the building to the destination center is selected by each agent.
2. The path segments which are selected by each agent are marked by an agent per each agent's passage.
3. The number of the agents which use from each path's segment is calculated by the counter mechanism. If the number of agents which use from each path's segment overtime is exceeded more than a trail formation threshold value, the segment will be converted to a line segment (as a track of personal trail).

When a trail with the least cost is formed between the building to the destination center:

4. The attraction force of the nearest path (in each side of the minimum cost trail) is calculated by an agent in the starting point of each segment of the path.
5. The attraction force of two adjacent paths is compared and the maximum attraction force is selected. The maximum attraction force value is compared with the effective attraction force threshold.

If the maximum attractions force value is less than the effective attraction force threshold:

6. The agent marks the segment and goes to the next starting point of the next segment in the minimum cost trail to the destination center.

If the maximum attraction force value is more than the effective attraction force threshold, the agent deviates from the minimum cost trail to attractive path with following mechanism:

7. The agent selects the next node based on the result of the direction finding mechanism.
8. The agent marks the segment between the current node the next selected node and go to the next node.
9. The agent calculates its new direction based on the result of the direction finding mechanism.

This process continues until the agent reach to the node on the path which attracts an agent. After that the agent passes from the existed path to the destination center.

10. If the number of agents which use from deviated path's segment is exceeded more than a trail formation threshold value, the segment will be converted to a line segment (as a segment of the personal trail).
11. In the process of the trail formation towards the destination center, when the number of agents which use from each segment is decreases from the trail formation threshold value over time, the trail segment is demolished and deleted from the infrastructure.
12. If the number of the agents which use of each personal trail segment is exceeded more than a defined value, the personal trail will be upgraded to collector trail.

4.12. Model agent

The household members who want to reach to the destination center from the settlement are the agents of the model. The agents have different economical status, gender and age. They choose the different destinations based on their activity plan.

4.13. Agent's behavior

4.13.1. Finding the closest node of the infrastructure grid structure to the house

The agent finds the closest node of the infrastructure grid structure from the center in the outside border of the settlement. The agent will find the least cost path from this node to the closest node to the destination center. The destination center is defined based on the output of the travel demand model which is the travel activity table.
The travel activity table of the individual is defined per each day and the location of the activity area is mentioned per an activity.

4.13.2. Finding the least cost path

The agent finds the least cost path from the center in the outside border of the city to destination center. The agent cannot pass from the high cost areas like physical barriers, pre-built houses and the areas with slope degree more than the acceptable range of slope degree in the landscape. In the process of finding the least cost path, the agent likes to pass from the areas which are placed in the suitable range of slope degree.

4.13.3. Calculation of the attraction force from the nearest paths

The agent likes to deviates to the nearest attractive path which reaches to the destination center. For this goal the agent checks nearest path (with the minimum Euclidean distance) in each side of the segment which reaches to the destination center at the starting node of each segment.

In the starting point of each segment, the attraction forces of the nearest paths are calculated by an agent.

4.13.4. Finding the suitable path for integration

The agent compares the attraction force of two adjacent paths and the maximum attraction force is selected. The maximum attraction force value is compared with the effective attraction force threshold. In case that the maximum attraction force value is more than the effective attraction force threshold, the agent deviates from the minimum cost trail to attractive path. When the agent starts the deviation it will only check the attraction force of the attractive path.

4.14. General model rules

4.14.1. Calculation of the link's (trail segment) impedance

The link's (trail segment) impedance (cost) for finding the least cost path is calculated based on the section 4.10.1 and 4.10.2.

4.14.2. Trail demolition mechanism

The counter counts the number of agents (N) who use from each segment. If the trail is abandoned or the number of the trail segment users decreases from the trail formation threshold value, the trail will be demolished because of the environmental factors such as weathering over time. In proposed model the decay function is the function of time. The decay function D (t) can be defined as following:

$D(N, t) = \sum_{1}^{t} N - D(t)$

Where:

N: number of agents who pass from the segment.

t: time passing from the beginning of the simulation

D (t): decay function, which it is the function of time.

If number of agents which use from each segment exceeded more than a trail consolidation threshold value, the segment will be consolidated and cannot be demolished or deviate latter.

4.14.3. Selecting the next node in the path deviation process

When the walking direction of the agent is calculated (which is in the direction of the resultant force of two attraction forces which are exerted on agent), the agent selects the next node for walking based on the following process.

The first figure in Figure 4.12 illustrates the grid infrastructure structure. The second figure in Figure 4.12 shows the typical situation of the agent who is placed on the node G (The node G is the example of the nodes which is placed on the corner nodes of the grid). The bisectors of the angles of HGC and CGF divides each angle to two equal 22.5 degree angles .The walking direction vector of the agent can place in one of these 4 sectors based on the walking direction vector angle with the horizontal axis. For example if the walking direction vector of the agent has a degree of 0 to 22.5 degree it placed in the sector of FGC. The nearest node to this sector is the node F. So the agent selects the node F and walk to it. The green letters shows the next selected node for the cases which the walking direction vector is placed in the respective sectors. The third figure in Figure 4.12 shows the case which the agent is placed in one of the non corner nodes like O in the grid structure. The green letters shows the next selected node when the walking direction vector placed in the respective sector.

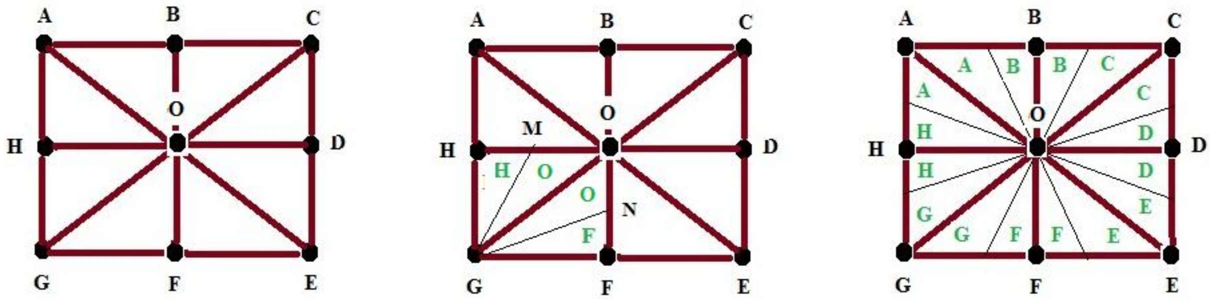


Figure 4.12: Finding of the next node in the process of agent deviation from the path

4.15. UML diagram of informal growth of infrastructure

The following figure illustrates the UML diagram of the proposed conceptual model for informal growth of infrastructure which includes two components of informal infrastructure model and the proposed housing model by Iqbal (2009) (Figure 4.13). The class attributes and methods of the housing model are adopted from Iqbal (2009).

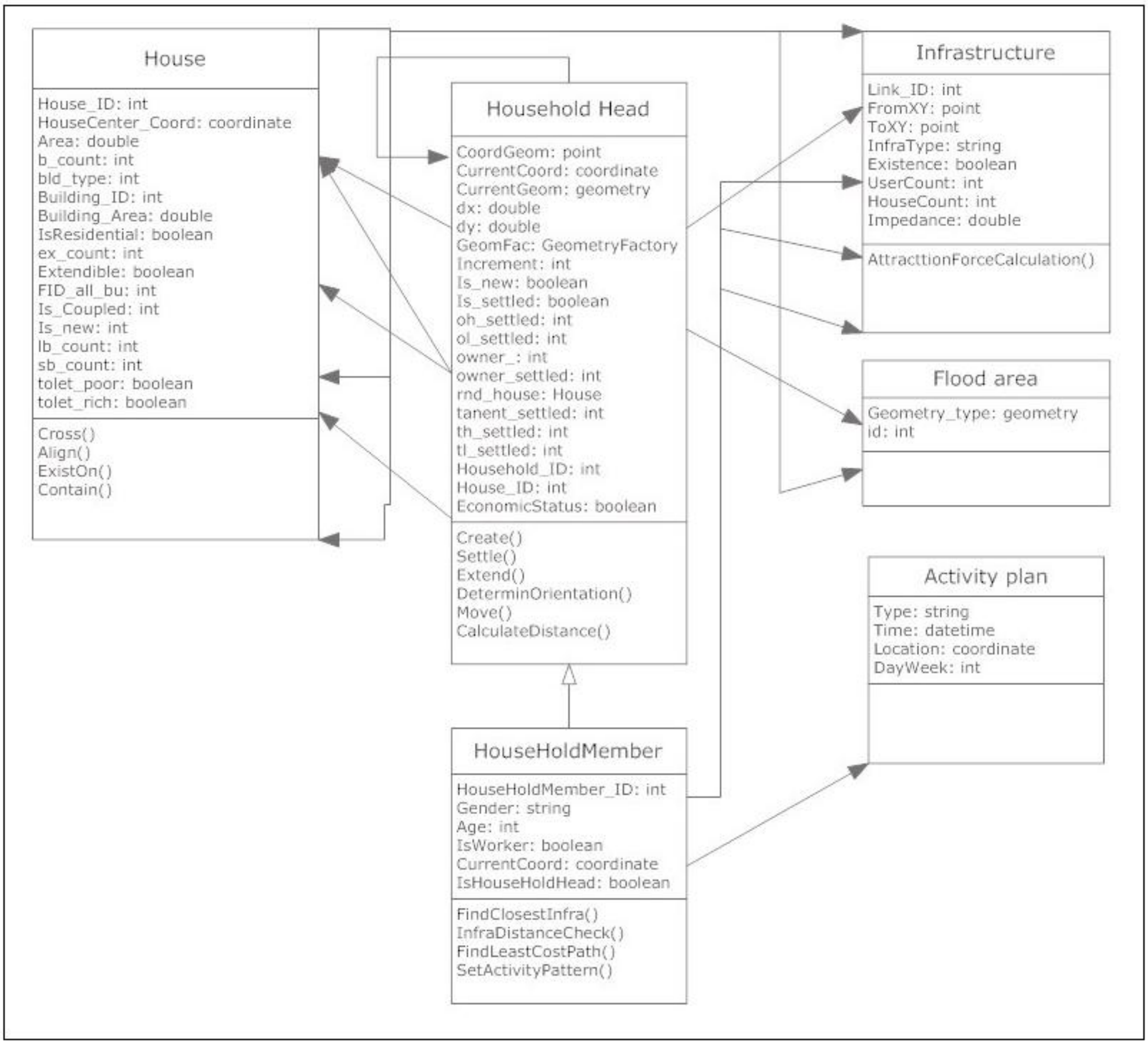


Figure 4.13: UML diagram of informal growth of infrastructure

5. Prototype Results and Evaluation

5.1. Introduction

In this chapter the results of the implemented prototype model will be evaluated. The prototype is designed to study the concepts proposed in the chapter 4. The prototype only includes the first component of informal growth model, for the personal and local trail formation for providing the accessibility of the buildings to the formal infrastructure and collector trails. In the following sections first the structure of the prototype model will be introduced. After that the prototype results will be evaluated and discussed.

5.2. Model prototype implementation

The concepts behind the first component of the informal trail growth model will be implemented in the prototype model. The steep slopes, physical obstacles and barriers are considered as very high cost areas in this prototype model. As a building is created in the model, it will be changed to the very high cost area and the infrastructure cannot pass from it. The prototype model builds a least cost path from the created house to the existed infrastructure. However, the gradual process of the trail formation is not considered in the prototype model and as a building is created, a trail will be built to provide the accessibility of the house. Also the upgrading process of the personal trail to the local trail is not considered in the prototype model. In the following sections, first the data preparation step for the prototype implementation will be described. After that the implementation structure and the prototype results will be discussed.

5.2.1. Data preparation:

The first step for implementing of a prototype for simulation of informal growth of personal and local infrastructure in Dar es Salaam is data preparation. To approach this, the essential GIS layers were prepared in ArcGis software. All required data layers were prepared in WGS84 projection system.

The infrastructure layer which contains the formal infrastructure and collector trails in the study area was prepared in Esri Shapefile format. The slope layer was clipped to fit it to the study area. The slope values were reclassified in to 3 classes: the slope degrees which are equal or less than the suitable range of trail's slope degree, the slope degrees which are greater than the suitable range of the slope degree but less than or equal to the maximum acceptable trail's slope degree and the slope degrees which are greater than the maximum acceptable trail's slope degree. The values 0, 3, 100000 were assigned to these three classes respectively. The river and the swamp which are located in the study area were selected in ArcGis. A buffer was created around the river and the swamp with the distance of 0.95 m and 1.65 m respectively, based on the results of the analysis in chapter three. These polygon layers were converted to the raster format in ArcGis and reclassified in to two classes. The value 100000 was assigned to the areas which are placed in the river and swamp and the value 0 was assigned to other areas. Three raster layers of slope, river and swamp were added to each other in ArcGis and the output raster layer was produced. The output raster layer was reclassified to produce a cost layer. The value 1 was assigned to the areas which had value 0, the value 3 was assigned to the areas with the old value of 3 and the places with the value of 100000 or greater, was reclassified to the value of 100000. And finally, a polygon layer which consists of the areas with the cost of 1 or 3 in the study area was produced.

5.2.2. Implementation structure

The prototype was implemented in ArcGis model builder. One point is produced randomly in the study area in each step which represents a new house which is built in the study area. The least cost path from a house to the existing infrastructure is created as polyline. As the buildings are supposed as physical obstacles, at the end of each step, the point is converted to a 10*10 raster cell .It is reclassified and will be added to the cost layer as an obstacle. The new infrastructure segment which is built in each step will be added to the previous infrastructure layer (Appendix A).

5.2.3. Prototype results

Two areas from the study area were selected (Figure 5.1 and Figure 5.2). This first selected area was chosen because the previous study on the modelling of informal settlement growth was done by Iqbal (2009) in this area. The second area was selected as there are swamp, river and the locations with the slope degree more than the maximum acceptable trail's slope degree. This provides the capability of studying of the influences of these features on the informal growth of trails in the prototype model. The model was run for 100 iterations for these two areas.

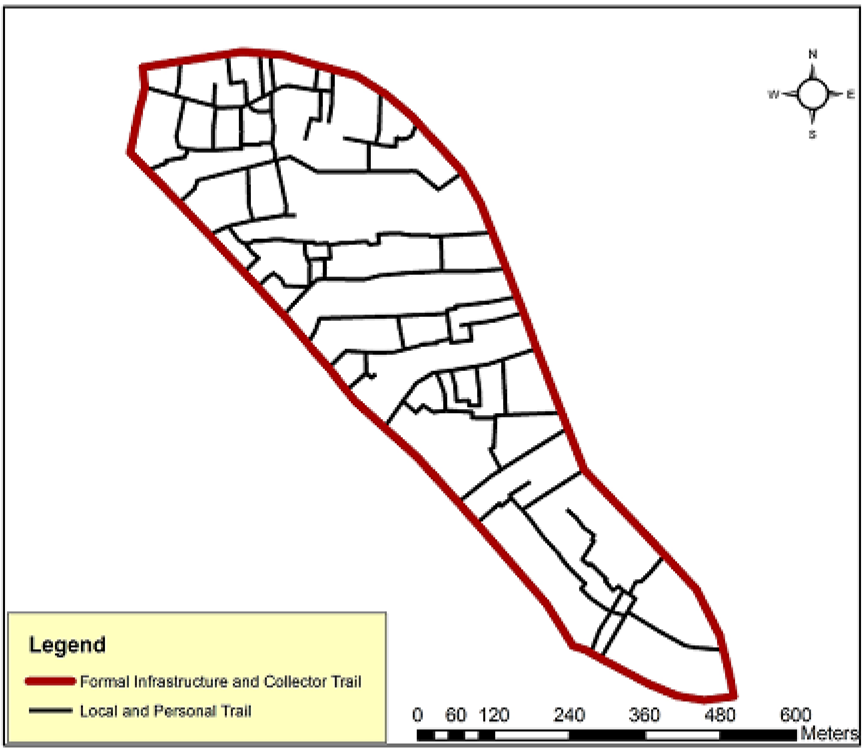


Figure 5.1: The selected area (area 1) for implementation of the prototype

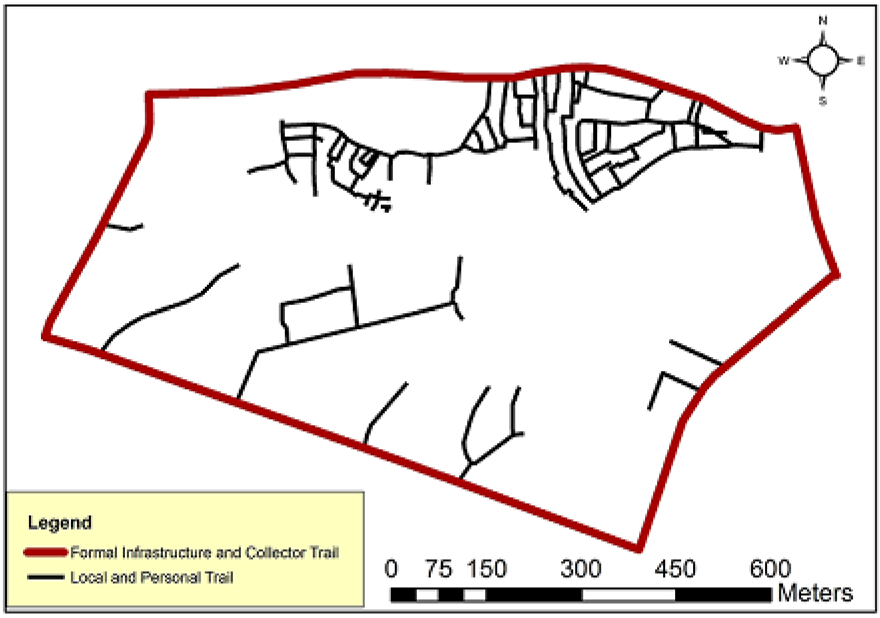


Figure 5.2: The selected area (area 2) for implementation of the prototype

The existed formal and collector trails were loaded as input to the model and the local and personal trails were modelled as the results of the implementation. The Figure 5.3 and Figure 5.4 shows the results of the model running for 25, 50, 75 and 100 points. As ArcGis uses the raster structure for calculation of the least cost path, some undershooting or overshooting can be emerged in the results of the implementation.

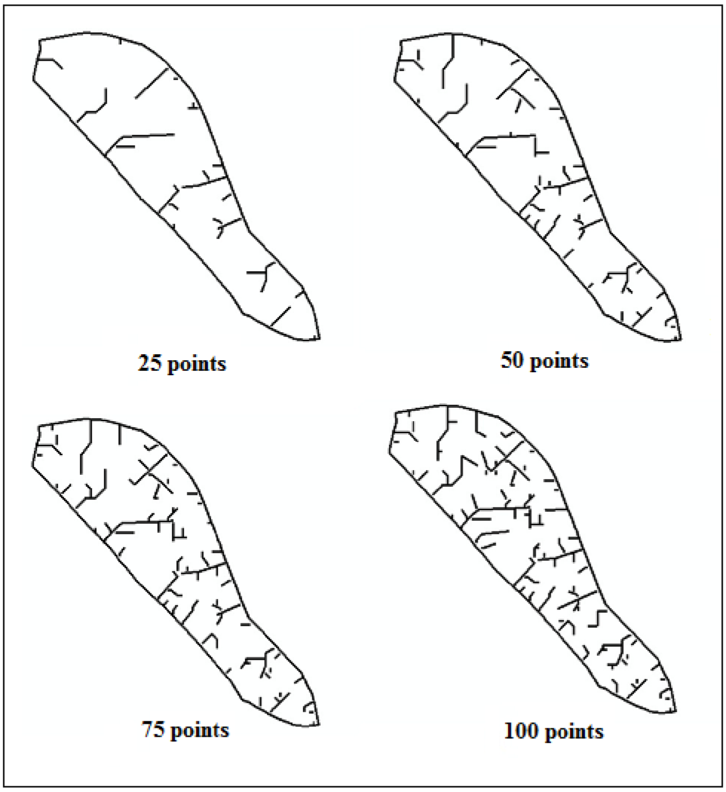


Figure 5.3: Results of the model running for 25, 50, 75 and 100 points in area 1

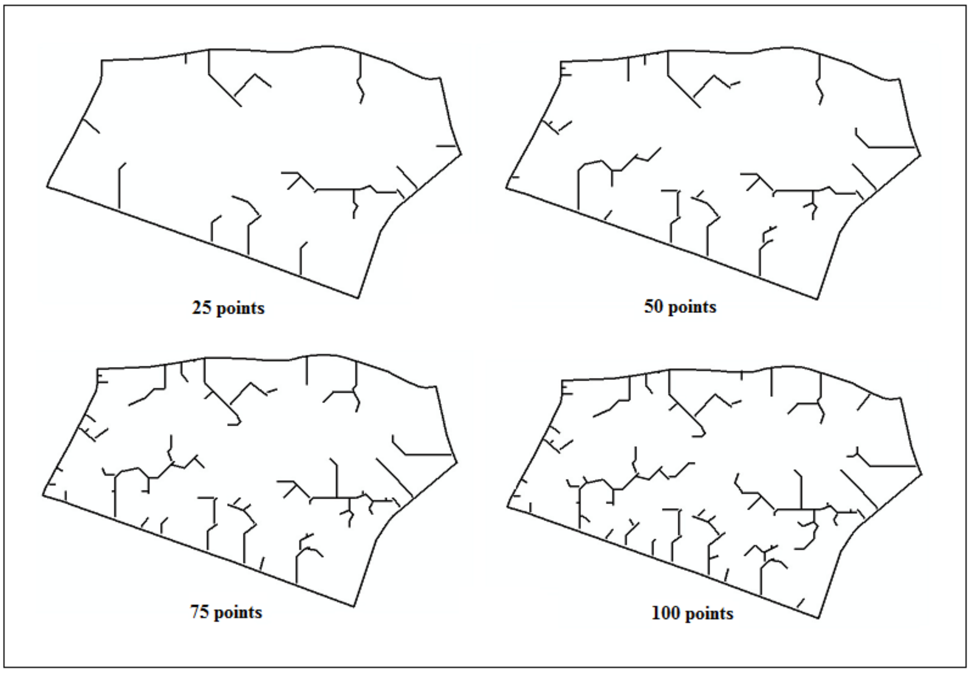


Figure 5.4: Results of the model running for 25, 50, 75 and 100 points in area 2

5.3. Model prototype evaluation

5.3.1. Total length and density of the local and personal trail

The Table 5.1 and Table 5.2 shows the total length and the density of the local and personal trails for prototype model (for 25, 50, 75 and 100 points) and also the respective values in the reality in the area 1 and 2.

	Total Length of the Local Trail and Personal Trail (m)	Density (m/m^2)
25 points	1089.7	0.008
50 points	1816.8	0.014
75 points	2261.2	0.017
100 points	2802.6	0.021
496 houses (Reality)	6216.5	0.048

Table 5.1 : Total length and density of the local and personal trails in the area 1

	Total Length of the Local Trail and Personal Trail (m)	Density (m/m^2)
25 points	1983.4	0.003
50 points	3101.3	0.005
75 points	4310.5	0.008
100 points	5077.1	0.009
1986 houses (Reality)	9501.7	0.018

Table 5.2: Total length and density of the local and personal trails in the area 2

As it is obvious in the both tables, there is an increase trend in the values of the total local and personal trail length and the density in the prototype iterations in the areas of 1 and 2. Also the value of the total length of the local and personal trail and the density of them in the reality is more than the results of the prototype in both areas.

5.3.2. Fractal dimension

The fractal dimension of the infrastructure in the area 1 and 2 was calculated for the prototype model's runs and the the existed infrastructure in the reality. Figure 5.5 and Table 5.3 illustrate the fractal dimension value for the local and personal trail in the area 1 in the reality and the different runs of the prototype and the Figure 5.6 and Table 5.4 shows the respective fractal dimension values for the area 2.

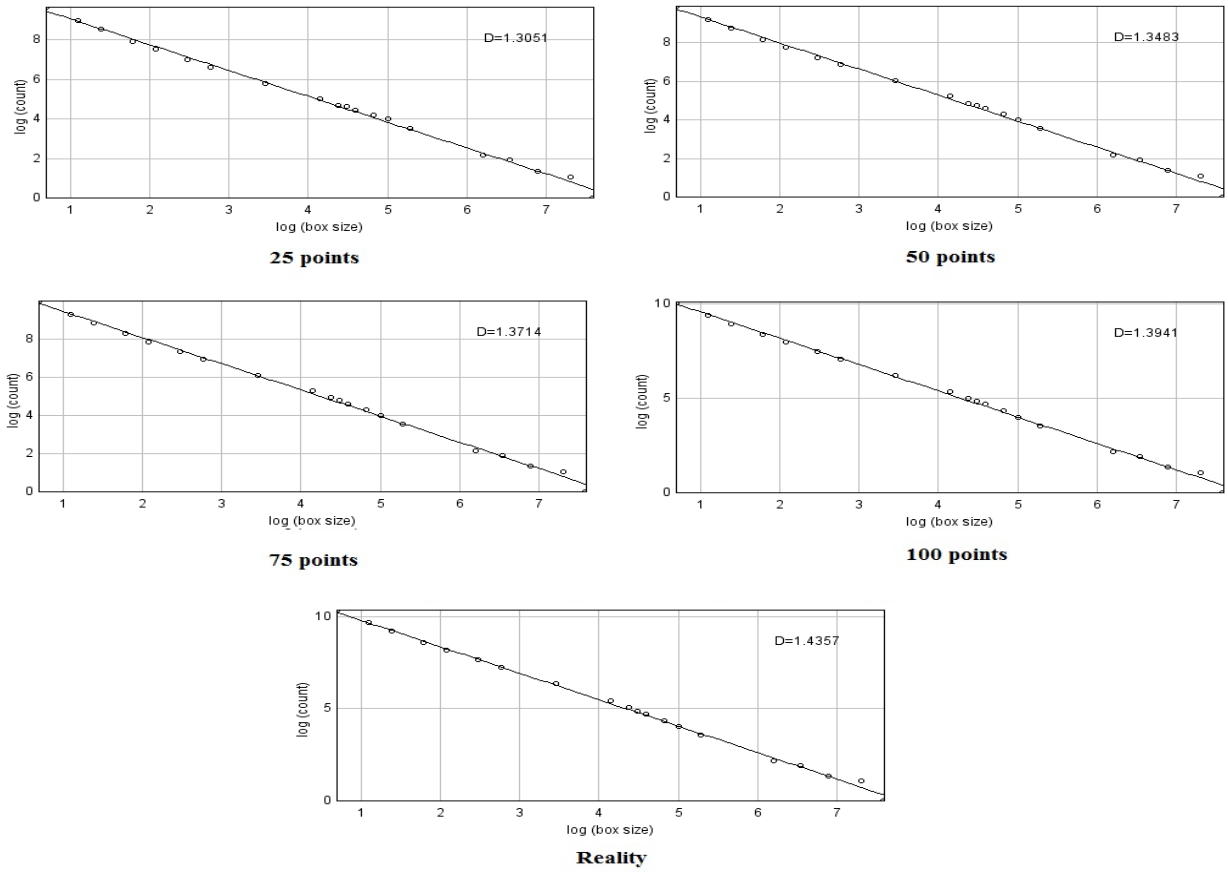


Figure 5.5: Fractal dimension value for the local and personal trail in the area 1 in the reality and the different runs of the prototype

	Fractal Dimension
25 points	1.305
50 points	1.348
75 points	1.371
100 points	1.394
496 houses (Reality)	1.435

Table 5.3: Fractal dimension value for the local and personal trail in the area 1 in the reality and the different runs of the prototype

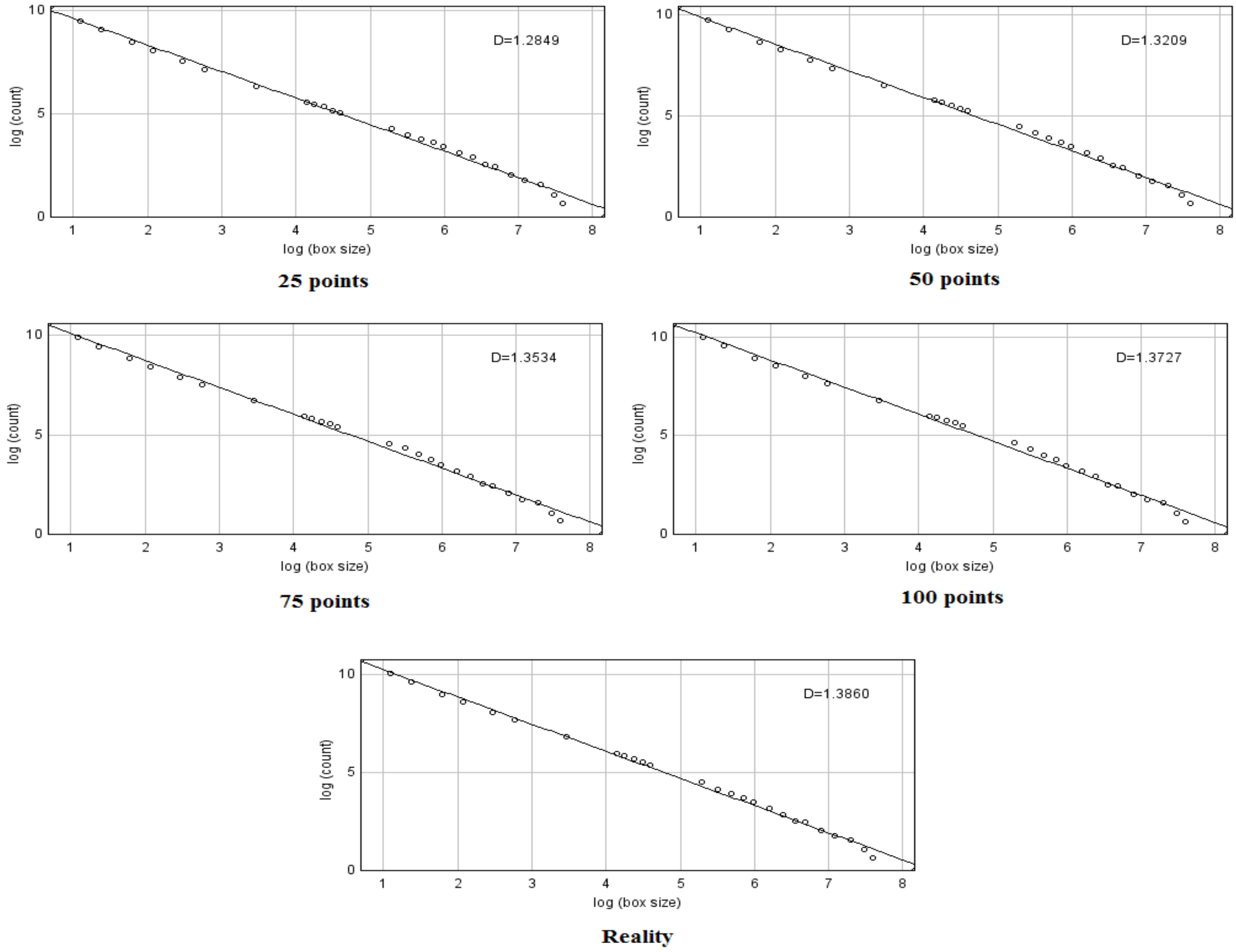


Figure 5.6: Fractal dimension value for the local and personal trail in the area 2 in the reality and the different runs of the prototype

	Fractal Dimension
25 points	1.284
50 points	1.320
75 points	1.353
100 points	1.372
1986 houses (Reality)	1.386

Table 5.4 : Fractal dimension value for the local and personal trail in the area 2 in the reality and the different runs of the prototype

The rising trend is observable in fractal dimension values of the prototype in 4 iterations. The fractal dimension of two areas in reality is more than the prototype values in the results of the prototype iterations.

5.3.3. Physical constraints and the local and personal trails configuration

In chapter 3 it was mentioned that the pedestrian has a preference for passing from the areas with slope degree equal or less than the suitable range of trail's slope degree. However, the pedestrian has a less preference to pass from the areas with the slope degree of more than the suitable range of the slope degree but less than or equal to the maximum acceptable slope trail's slope. The pedestrian avoids passing from the areas with the slope degrees greater than the maximum acceptable trail's slope degree or the physical obstacles and barriers.

As it was mentioned before the arbitrary cost value of 1 was assigned to areas with the suitable range of trail's slope. The arbitrary cost value of 3 was assigned to the areas which their slope degrees are more than the suitable range of the slope but less than the maximum acceptable slope. The cost value of 100000 was assigned to the areas with slope degrees more than the acceptable trail's slope degrees, the physical obstacles and barrier. However, more study should be done to find realistic cost values which is not conducted in this research according to the time limit.

The Figure 5.7 and Figure 5.8 illustrated the result of the prototype (for 100 points) and the local and personal trail in the reality in relation with the cost layer in the area 1 and 2.

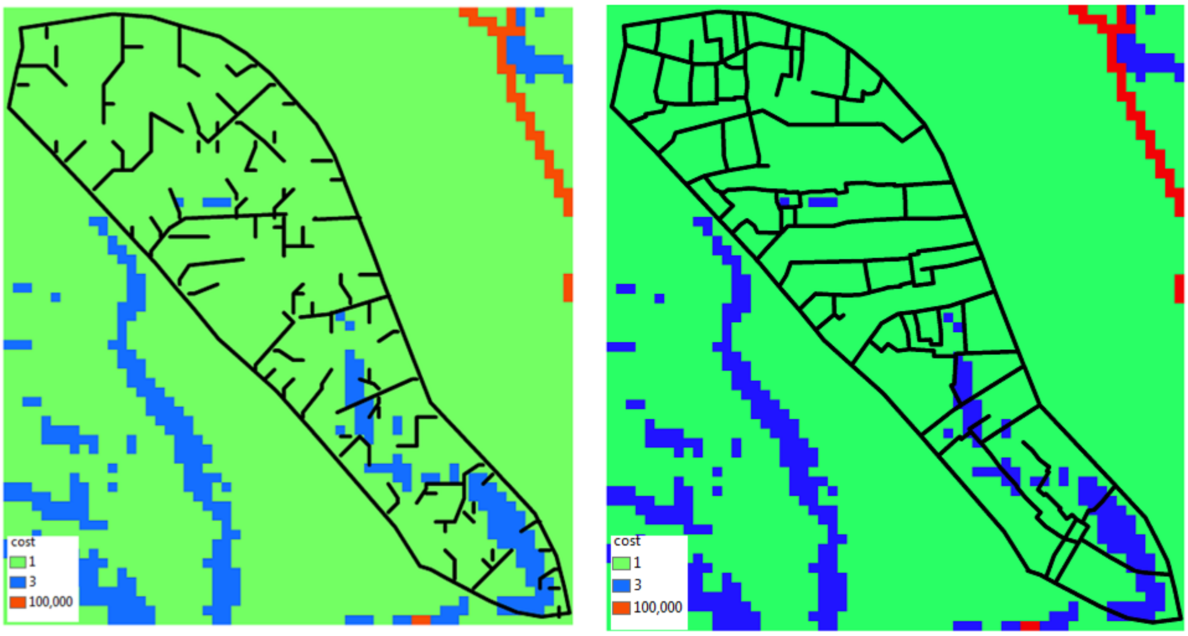
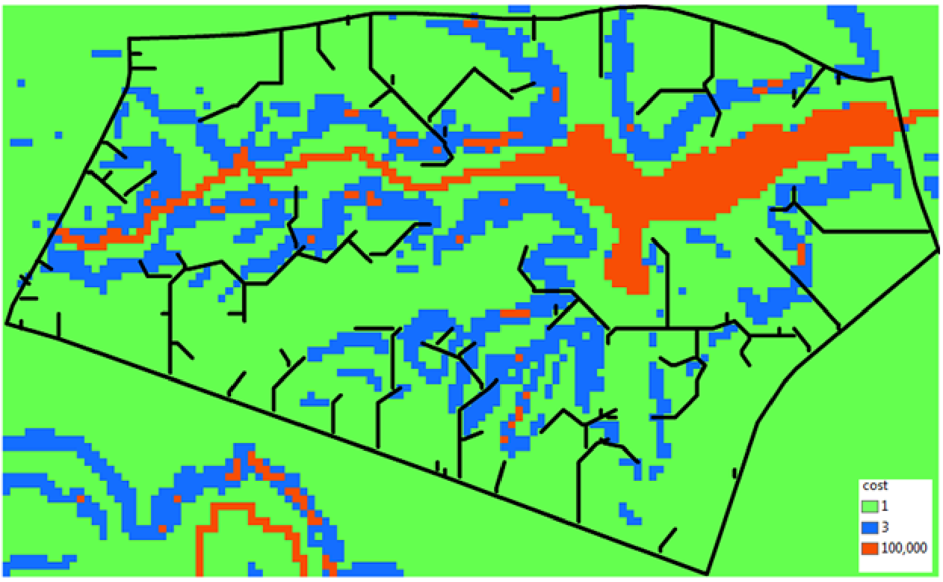


Figure 5.7 : The result of the prototype (for 100 points) (left), and the local and personal trail in the reality (right) in relation with the cost layer in the area 1



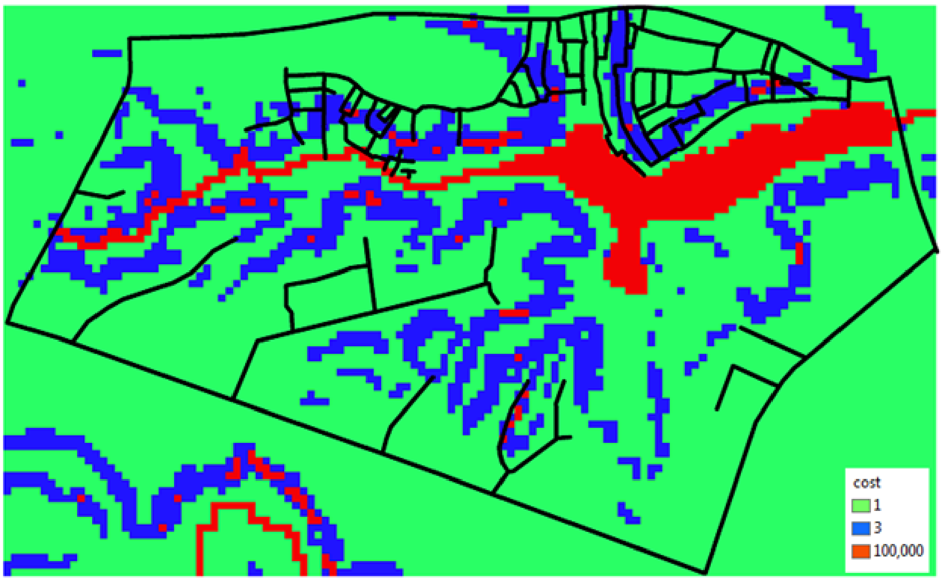


Figure 5.8: The result of the prototype (for 100 points) (top) and the local and personal trail in the reality (down) in relation with the cost layer in the area 2

Figure 5.9 and Figure 5.10 show some of the observed patterns in the result of the prototype (for 100 points) in area 1 and 2 which are similar to results of the analysis in chapter 3.

As the pedestrian prefers to pass from the suitable range of the slope, it avoids passing from the areas which have a higher degrees of slope, so the trail is stopped when it faced with the slopes with higher degree than the suitable range of the slope in most of the cases.

Also the pedestrian has tendency (if it is possible) to pass from the corridor like areas (the areas with the slope degrees in the suitable slope range which is placed between two areas with the slopes more than this range) instead of walking from the slopes more than the suitable slope range and equal or less than the maximum acceptable slope range.

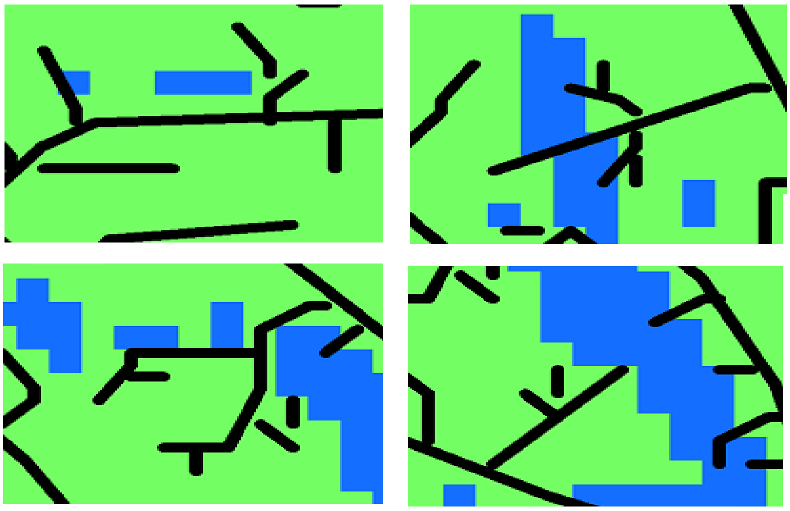


Figure 5.9 : Some of the observed patterns in the result of the prototype in area1

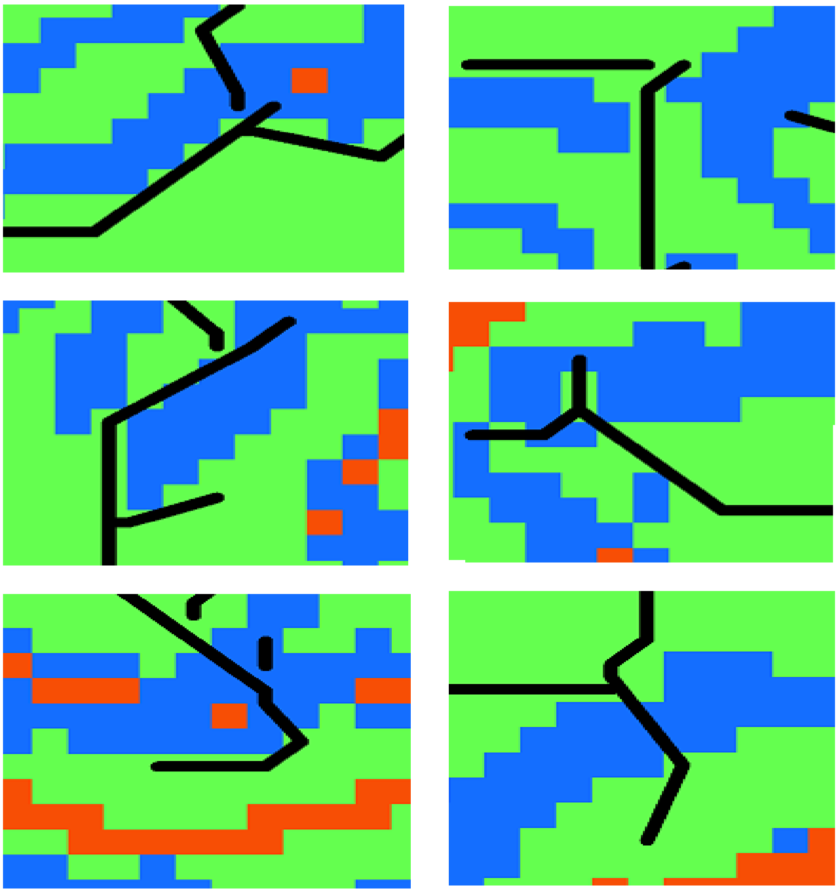


Figure 5.10: Some of the observed patterns in the result of the prototype in area2

To find the amount of personal and local trails which pass from the areas with cost value of 1 and 3, the personal and local trails were converted into equidistant points (with 1 meter intervals) in each case. After that, the cost value of each point was extracted. Table 5.5 and Table 5.6 show the number of points from the local and personal trails which pass from each area (with cost value of 1 or 3) and their respective percentage of it (in comparison with the total number of points which form the local and personal trail in each case) for prototype model (for 100 points) and in the reality in the area 1 and 2.

Area1	Cost: 1		Cost: 3	
100 points	2736 points	96.79%	91 points	3.21%
496 houses (Reality)	5698 points	89.74%	652 points	10.26%

Table 5.5: The number of points from the local and personal trails which pass from the areas with cost value of 1 and 3 for prototype model (for 100 points) and in the reality in the area 1

Area 2	Cost: 1		Cost: 3	
100 points	4810 points	91.52%	446 points	8.48%
1986 houses (Reality)	8057 points	85.88%	1325 points	14.12%

Table 5.6: The number of points from the local and personal trails which pass from the areas with cost value of 1 and 3 for prototype model (for 100 points) and in the reality in the area 2

As it is obvious in the Table 5.5 and Table 5.6, there is more preference for the individuals to pass from the low cost areas.

5.3.4. Discussion

The total length of the local and personal trails (in the prototype results and the reality) in the area 2 is more than the area 1. However the respective density values of the local and personal trails in area 1are more than the area 2. One of the main reasons of this issue is because of the large area of high cost locations in the area 2. In the reality, as the households more prefer to build their houses in the flat or near flat areas, the local and personal trails are more developed in these areas in the first stages of the informal settlement (when the main portion of trails are formed in the settlement). The high cost areas (more than the cost value of 1) in the area 2 prevent the development of the local and personal trail in all parts of the area. So, the local and personal trail density value of the prototype model is less than the respective value in the same iteration of run of the prototype model in area 1.
The fractal dimension is good criterion for evaluation of the complexity and amount of the growth (maturity) of urban patterns. As the density of the local and personal trails in area 1 is more than the area 2 (because of the preference of the residents to build in this area in the first stages of the informal settlement starting in this zone) the maturity and the development of the infrastructure (local and personal trails) in this area is more than the area 2. So, the respective fractal dimension of the infrastructure (in the reality) in area 1 has greater value than the area 2. Also as the densities of the local and personal trails in area 1 in the prototype model are more than the respective value in the area 2 (in the calculated iterations) the fractal dimension value of them are more. Sun, et al. (2007) calculated the fractal dimension for some developed urban infrastructures in the U.S cities which are around 1.7. The difference between the fractal dimension of these two areas (in the informal settlement) and the calculated fractal dimension for the developed urban infrastructure indicates that the infrastructure is not mature and developed well in the informal settlement. This underdevelopment in the infrastructure of the informal settlement reduces the service quality of the infrastructure to the residents.
The prototype model distributes the point (which is the representative of the house) randomly in the area.

In the first stages of the informal settlement in the reality, the houses are built besides existing infrastructures (mainly formal infrastructure and collector trails) or in the near relative distance to them. Some of the households prefer to construct their buildings close to the pre-built buildings beside or near existing infrastructure while some of them prefer to built their buildings in the random manner (relatively far from the existed buildings) but beside or close to existing infrastructure. As the settlement develops and the local trails and personal trails are grown, the new households are directed to build their buildings beside or near existing trails (which were built by the previous households). They fill the empty spaces between the houses which are built beside the trails. In these ages of the settlement growth, the trails formation process is continue. The new personal trails will be developed to provide the accessibility of the houses to the higher ranks of infrastructure in the hierarchy. Also some of the local trails can be built or developed in this stage of the informal settlement. In the last stages of the settlement the infilling process will be happened. In this stage, there is not an enough time and space for the formation and development of the trials and the new residents use from the spaces between the houses to reach to the existed infrastructure.

The time period of emerging of these 3 steps of informal settlement growth is based on the different social, economical and environmental factors which can have influence on the settlement dynamics.

For example in the north east of part of the area 2, the personal trails developed more than the local trails (Figure 3.2). This is because of the fact that as the settlement is developed in the area 1, the area 1 became more attractive for the settlement of the new settlers. In the last stages of the settlement, as there is not enough space for all the settlers for building the new houses in the area 1, some of the new settlers are were prefer to build their house adjacent to the area 1. So, the overflow population of the new settlers will construct their houses in the north east of the area 2 in the short time (which is close to the area 1). This rapid dynamic causes that the local trails cannot be formed and developed with the considerable length.

After this, the new settlers continue the construction of the new buildings in the other parts of the area 2. As this phenomenon has a very rapid speed, the trail formation process is not formed well, in the north west of the area 2. As it is obvious, the simple implemented prototype model does not consider the complex dynamics of the informal settlement.

6. Conclusions and Recommendations

6.1. Conclusions

The objective of this research was to develop an agent based model to simulate the informal growth of infrastructure in Dar es Salaam, Tanzania. Informal settlements have a complex nature caused by different dynamics that are available in the informal settlement process. These dynamics influence each other, which causes an increase in the complexity of the system. This complexity leads to emerging complex aggregated patterns in the settlement. To understand these complex patterns which are emerged in the context of informal settlement, the study of the driving forces which create these patterns is necessary.

To analyze the driving forces which influence the growth of infrastructure of informal settlement in Dar es Salaam, first the infrastructure classification system was proposed to differentiate the different types of infrastructure. The analyses of driving forces were formulated in three categories, relationships between infrastructure and the environment, the geometric structure relationships in infrastructure and the relationship between buildings and infrastructure.

In the first category of the analyses, the relationship between infrastructure and environment was studied. The infrastructure relationship with topography and barriers were studied in this level. Results of the analyses on the topography (in the relationship with trails) show that the infrastructure avoids passing from the steep slope. For the less steep slopes, it can be often seen the infrastructure pass from the certain range of slope degree. To provide the criteria for the influence of the slope on the trail formation, the maximum acceptable slope and the maximum suitable range of slope were defined for each type of trails. The barriers can influence the growth of infrastructure too. It is not easy to cross a river and swamp. So, this type of features has an impact on the infrastructure in its vicinity. The study shows that the lower level of infrastructure (personal and local trail) cannot pass from the river. However, the collector trail and formal infrastructure can pass from the river when it is possible to build a bridge on the river. The study indicates that the swamp stops all types of the infrastructure. Also it was proved that the infrastructure pattern in the non flood prone areas and flood prone areas are the same.

In the second category of the analyses, the geometric relationships in infrastructure were studied. This is of a different type compared to the influences in the first category as this is not about a driving force but about a characterisation of the infrastructure itself. In this research an attempt was made to come up with different types of measures that can describe and quantify the infrastructure structure. The geometric regularities were studied in three headlines of infrastructure structure, angles and the length of infrastructure. The study on the infrastructure structure shows that the collector trails connect to the formal infrastructure and make a deformed grid structure. This deformed grid network is divided the zone in to the deformed semi-rectangular-like areas (settlement blocks). This grid of formal infrastructure and collector trail is formed to ease the collection of the trips from the local and personal trails which are placed inside the settlement blocks. The other study on the infrastructure structure indicates that the pro-Steiner like structure can be observed in collector trails. The average intersection angles of the infrastructure were calculated in ten classes based on the different types of infrastructure which participate in the intersection. This study shows that the average intersection angle increases by the increase of the infrastructure ranks which participate in the intersection. The only exception in the exception is the intersections of the two personal trails which is more than the average intersection degree of formal infrastructure and personal trail. The results of the study on the average length of four

types of infrastructure segments show that the highest level of infrastructure (formal infrastructure) has the longest length of segments. There is a decrease trend in the respective value of the average length of the trail segments and the lowest level of infrastructure (personal trail) has the shortest length of segments in the infrastructure hierarchy.
In the third category, the relationship between buildings and infrastructure was studied. A new house can lead to a new trail, as the occupants of this house need to 'reach' different places, but the opposite process also can occur. A new infrastructure can make a site accessible and therefore more attractive to new settlers. This category of the study led to divide the process of informal infrastructure growth inside the settlement into three time stages based on the three stages of informal settlement growth. The local trails are formed inside the settlement in the first stage of informal settlement growth. In the middle stage of the informal settlement development, the personal trails are mainly developed. However, as the process of the densification by the new settlers has a rapid nature in the last stage of the informal settlement growth, no trail have an enough time to be developed in this stage.
The results of the different analyses on the driving forces, lead to understand there is not only one dynamic in the process of informal infrastructure formation. The two different mechanisms of infrastructure development were identified as:

- Local and personal trail formation mechanism
- Collector trail formation mechanism

The first mechanism which plays the main role in the formation of local and personal trails inside the informal settlement is based on the needs of the residents for providing their accessibility to the higher ranks of infrastructure in the infrastructure hierarchy (formal infrastructure and collector trail).
The collector trails are formed based on the second mechanism. The residents will have to reach the different destinations to perform their daily activities. This can lead to form the collector trails.
Based on the findings of the analysis of the empirical data of Dar es Salaam two different models were proposed to model these different mechanisms.
In the first model the houses connects to the formal infrastructure or collector trails (directly or by the means of the existed infrastructure) with the minimum cost path. When the number of individuals who use the path exceeds more than a pre-defined threshold a personal trail is created. In the proposed model, when the number of houses which use from the personal trail exceeds more than a pre-defined threshold, the trail will be upgraded to the personal trail.
The second model is proposed for modelling of the collector trail formation. In this model the collector trail is formed from the settlement to the destination to provide infrastructure for the residents to perform their daily activities (for example going to work or school or perform household activities like collecting water). The pedestrians consider two factors in the travelling to the destination (avoidance of obstacles and slopes and a preference for established roads). First, the pedestrians avoid passing from the area with unsuitable range of slope degree (steep slope) and the physical obstacles and barriers and they have a tendency to reach to the destination with the least possible distance. The second factor which is considered by the pedestrian is that they like to benefit from the advantages of the existed consolidated paths (as they have a better surface for walking) and high used paths (which caused the pedestrians to feel more safe).
The proposed model considers the two above mentioned factors and is developed to model the path diversion process of the collector trails to the consolidated and high used adjacent path (with the same destination to the destination center). The deviation process of the trail is modelled based on the attractiveness of the adjacent attractive path for taking the advantage of it and reaching to the destination center for pedestrians in the same time.

The prototype model was developed for evaluation of the concepts behind the first component of the informal infrastructure growth model. The implementation was done to evaluate whether the concepts behind the first component of the model can emerge the similar pattern as reality. Two different areas from the study area were selected and the prototype model was run for them. The configuration of the prototype model's result for the area 1 and 2 shows that the similar patterns to the reality can be seen in the prototype's results.

The results showed that the accuracy of the model is highly depending on the consideration of three stages of informal settlement growth. In the first area, as the first and second stages of the informal settlement were developed with the gradual speed of growth, the local and personal trails have formed and developed in all parts of the area. In this area the density of the local and personal trail is 0.048 (m/m^2) and the respective fractal dimension value for the infrastructure is 1.435. In the second area, as the settlement had a rapid characteristic, the first and second stages of the settlement were developed in the short period of time. As a result of this, the personal and local trails are not developed in all parts of the area.

In the second area the density of the local and personal trail is 0.018 (m/m^2) and the respective fractal dimension value for the infrastructure is 1.386. The study shows that for achieving the satisfactory results in the simulation of the local and personal trail, the model must consider the different speed of informal settlements growth in the different areas which is based on the different social, economical and environmental factors. Consideration of the settlement growth speed factor causes to understand when the process of the local trail and personal trail formation stop.

The comparison between the calculated fractal dimension for these two areas (in the informal settlement) with the fractal dimension for developed cities (1.7) shows that the development of the infrastructure in the informal settlement is poor. This poor development and distribution of the infrastructure in the informal settlement causes the low quality service of the infrastructure in these areas.

6.2. Limitations

There are several limitations existed in this study. The first category of the limitations in this research is the lack of data. In the phase of analysis of the infrastructure growth driving forces the lacking of the data caused some limitations. It was not possible to develop the extent of the study area for analyses of the infrastructure driving forces as the road and footpath data was available only for the introduced area. The image time series and the infrastructure layers which show the infrastructure development during the settlement growth in the study area was not accessible. The data on soil type, seasonal wetlands and width of the river are not available. Also the data on the economical centers and the service areas (such as clinics, schools and water pumps) which has an influence on the formation of the infrastructure was not available. Not all of the driving forces that may influence on the informal growth of infrastructure were considered, for example the gender of the pedestrian may have influence on the process of the informal infrastructure formation. The developed model also has some limitations. The presented model uses from the grid structure for the infrastructure environment. This assumption is not true in the reality. However as the cell size of the grid decreases, the more accurate results can be gained. The proposed models do not consider the randomness in the walking process of the pedestrian. This can influence the results of the simulation. The proposed informal infrastructure growth model has some parameters which need to be calibrated; this takes a long time which is not feasible to do in the limited time of doing a MSc. thesis. The proposed model's component for collector trail growth does not consider the housing process beside the trail which prevents from the gradual deviation in the trails path. There are some limitations in the prototype model. Only two areas are selected in this study. There was not a realistic housing model in the implementation of the prototype model. Also very few houses were generated in the prototype model.

6.3. Recommendations for future work

The main output of this research is the conceptual model that was developed for the construction of an agent-based simulation model. The research shows that it is possible to extent the current housing model and proposes a solution of using a grid-network based environment that consists of both the existing infrastructure and potential future infrastructure as the basis of this model. The research also proposes mechanisms to enable agents to sense their environment and choose between existing and potential infrastructure to provide the accessibility of their houses to the formal infrastructure and collector trail and also to connect to the destination centers.

Due to time constraints and data limitations this model was not implemented. Before tackling the implementation it is essential to consider if data can be acquired to calibrate and validate this model. The available housing model should be adjusted to combine with infrastructure growth model. Generating trips for every household member to daily visited places would require very detailed and personal information that may not be obtainable. A solid plan is required to come up with a method for a realistic synthetic population with the required activity plans. So, as this research has covered some aspects of the complex dynamics of the informal growth of the infrastructure, this work can be improved to reach to the more generic and comprehensive model. Multiple research and development can be done in the future to achieve this goal. In the addition to above mentioned issues some of the other suggestions are described as following:

- The study was focused only on the limited driving forces of the informal infrastructure growth in informal settlement. The other issues such as the role of the pedestrian gender, the role of the seasonal wet lands, the soil quality of the area and pedestrian safety feeling in the path formation process can be studied.
- Designing the suitable trip generation and distribution model in the context of an informal settlement is important. This model can consider the multi activities of the pedestrians in the daily trips.
- In this study it was assumed that the pedestrian uses the least cost path in walking between two locations and without any randomness in the process of the walking. A research should be done to study the logic of the pedestrians in the informal settlement in finding the minimum cost path in the environment. The minimum cost path which is finding by the pedestrian may be slightly different from the prefect mathematical the least cost path. Also the factor of randomness can be entered to the model.
- As the proposed models have some parameters, they need to be calibrated. This can be done in the process of validation and calibration of the implemented model by the empirical data.
- The informal infrastructure growth model was proposed for the informal settlement in Dar es Salaam. More studies should be conducted to study if the proposed model is applicable in other informal settlements.
- The proposed model for the formation of the trails in the informal settlement can be combined with the previous proposed model for housing process in the informal settlement by Iqbal (2009). In this case the interaction and the influences of these two main elements of the informal settlement on each other can be simulated. To reach this goal the housing model should be modified to these two models merged properly. The housing model should consider the social tendency of the settlers to settle beside the existed houses. This model must be

developed to model the three stages of the informal settlement to proper way, which causes to simulate the informal growth of the infrastructure more accurate.

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Appendix A: Prototype model