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Queuing modeling to improve service in water systems

García Castañeda, R.

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Queuing modeling to improve service in water systems

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R. García Castañeda

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Student identity number: 0825503

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Supervisors:

dr. K.H. van Donselaar, TU/e, OPAC
Prof. dr. J.C. Fransoo, TU/e, OPAC
MSc. MBA Sergio Barbarino, P&G

TUE. School of Industrial Engineering

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Executive summary

This master thesis project is about improving the service in water systems by building queuing models. Currently, more than 1 billion people do not have access to safe drinking water and there are 2.6 billion people worldwide who do not have access to minimal level of sanitation according to the Human Development Report 2006. Considering this problematic, HumanNeeds Project (HNP) and Procter & Gamble (P&G) made a collaborative project to improve the situation concerning the lack of clean drinking water and sanitation, and to contribute with the development of the community in one of the largest slums of Africa: Kibera, Kenya.

Problem Statement

The amount of limitations involved while improving water systems in developing countries is high as a result of lack of infrastructure and unreliable systems. Information and data availability is scarce and difficult to obtain. Furthermore, there is a lack of models that evaluate water systems in developing countries, and that analyze operations in order to improve the service given to communities. The purpose of this master thesis was to determine the data required to understand operations in water systems, to make an analysis of the water center, to provide solutions to improve the service in water systems, and to compare the performance of analytical model and simulation model.

Analysis

Demand and service time's estimations were obtained for the analysis through consumers' research, surveys and data from several water points in Kibera. The analytical model with a steady state approach showed all the services with more than 90% of utilization. The service stations with the highest number of customers waiting were the Payment station, the Water Kiosk and the Hand Washing station with approximately 50, 33, and 12 people waiting respectively. Moreover, a simulation model was built to validate the analytical model. The simulation model was run for a long period of time using only the parameters of peak-hours to make the comparison with the analytical model. The results are validated since the utilization is almost the same and the longest queues are in the Payment system, the Water kiosk and the Hand washing station with 45, 39, and 11 people waiting respectively.

Contrary to steady state simulations, the Town center will have several arrival distributions depending on the time of the day (50% in the morning, 20% in the afternoon, and 30% in the

evening). Moreover, when the Town Center was simulated, the simulation length taken was 16 hours of operation. It was appreciated in the results that queues do not grow as in a steady state approach because the simulation length of the operational day does not allow congestion for long periods of time, thus, queues cannot increase to the level of a steady state approach.

Based on the day simulations, the period of time where the water center will have more congestion is in the morning with 3 critical stations: Payment station, Water kiosk and Laundry services with 23, 11, and 2 people waiting in line. Sometimes waiting time can be long like in the Laundry services with 30-50 minutes waiting time on average due to long service times.

Sensitivity Analysis

Some sensitivity analysis was performed assuming variations in the water system. On weekends, the queues are more noticeable and queues can grow really fast if the demand overall increases in approximately 30%. Furthermore, service times are important in the water system because they can cause congestion. In some situation where the employees have a shorter service time; management needs to allocate them to the critical stations to reduce queues in the system. Also, the number of people receiving payments can be decreased in the afternoon and in the evening to 3 and 4 respectively based on service times and the congestion in the system.

Furthermore, simulations were made where people leave the Town Center and go to other water points when the queues are long in the payment station. The results showed that on average the water center might lose 110 consumers per day if queues are long (20 or more people). Nevertheless, if there are 4 servers in the payment station instead of 5, the Town Center might lose 620 consumers per day, (10,218 KSH per day). This money represents 11% of the expected revenue per day or the salary of 10 staff employees per day.

Improvements & Feasibility

Number of servers

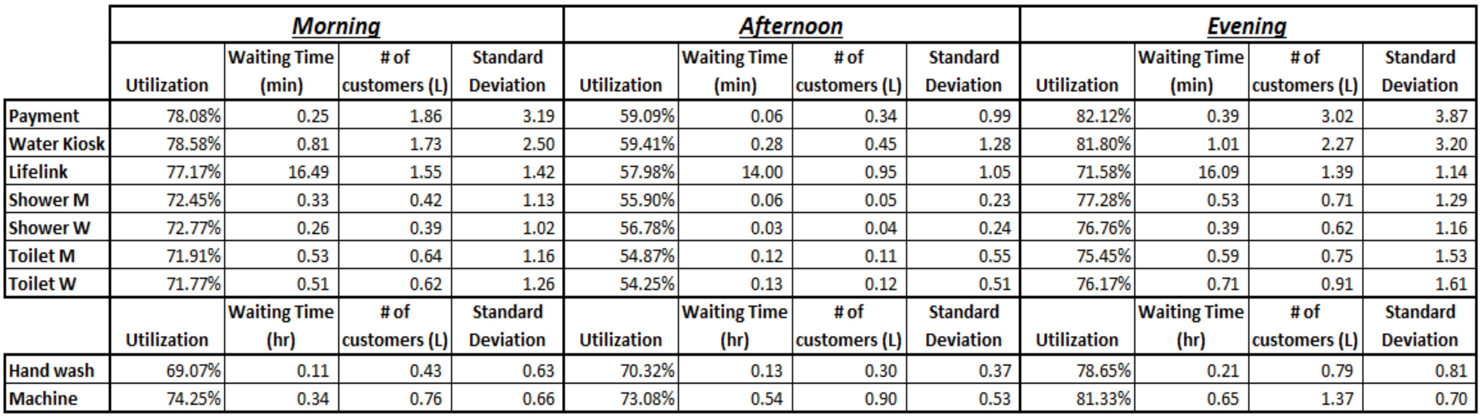
For the payment services, the Town Center needs 5 people to receive the payments but if there are some financial constraints to hire new employees; the management can increase the capacity by allocating more of the current resources. For the Water Kiosk, there is no room to install more taps but installing double hoses per tap is a feasible solution to increase the number of servers. For the washing machines more servers can be installed but the space available needs to be considered before buying new machines.

Top-up cards

Top-up cards are a solution for long queues in the payment station since the people will have money in their cards and they will go directly to the service stations, decreasing the number of people in the payment station. For example if 25% of the people have money in their cards, less people will go through the payment service reducing queues to 7 people waiting (initially 23 people waiting). Thus, the top-up cards help to decrease the number of people waiting in the payment station.

Balance the flow of people

The best solution when there are queuing problems is to balance the flow of people during the day. This can be done through promotions that encourage people to go to the water center at other times. Assuming HNP can decrease 10% of the demand in the morning shift, the distribution will be 40% of people going in the morning, 25% in the afternoon, and 35% in the evening, resulting in:



	Morning				***Afternoon***				***Evening***			
	Utilization	**Waiting Time (min)**	**# of customers (L)**	**Standard Deviation**	**Utilization**	**Waiting Time (min)**	**# of customers (L)**	**Standard Deviation**	**Utilization**	**Waiting Time (min)**	**# of customers (L)**	**Standard Deviation**
Payment	78.08%	0.25	1.86	3.19	59.09%	0.06	0.34	0.99	82.12%	0.39	3.02	3.87
Water Kiosk	78.58%	0.81	1.73	2.50	59.41%	0.28	0.45	1.28	81.80%	1.01	2.27	3.20
Lifelink	77.17%	16.49	1.55	1.42	57.98%	14.00	0.95	1.05	71.58%	16.09	1.39	1.14
Shower M	72.45%	0.33	0.42	1.13	55.90%	0.06	0.05	0.23	77.28%	0.53	0.71	1.29
Shower W	72.77%	0.26	0.39	1.02	56.78%	0.03	0.04	0.24	76.76%	0.39	0.62	1.16
Toilet M	71.91%	0.53	0.64	1.16	54.87%	0.12	0.11	0.55	75.45%	0.59	0.75	1.53
Toilet W	71.77%	0.51	0.62	1.26	54.25%	0.13	0.12	0.51	76.17%	0.71	0.91	1.61
	Utilization	**Waiting Time (hr)**	**# of customers (L)**	**Standard Deviation**	**Utilization**	**Waiting Time (hr)**	**# of customers (L)**	**Standard Deviation**	**Utilization**	**Waiting Time (hr)**	**# of customers (L)**	**Standard Deviation**
Hand wash	69.07%	0.11	0.43	0.63	70.32%	0.13	0.30	0.37	78.65%	0.21	0.79	0.81
Machine	74.25%	0.34	0.76	0.66	73.08%	0.54	0.90	0.53	81.33%	0.65	1.37	0.70

Table - Results of a balanced water center during the day

Balancing the flow of people is vital to smooth the operations in the water system, to reduce the congestion, and to prevent that people leave the water center because of long queues.

Performance measurements

Every system needs performance measurements to maintain operations under control and detect anomalies. The Town Center needs to have performance measurements to be able to understand the water system and control future operations. Management needs to measure the service times, the capacity and the number of people served per hour. This will help to obtain the utilization and to know if the capacity is being exceeded by the demand. If the capacity in the Town Center is topped and HNP cannot invest in new servers, a limitation needs to take place in the payment station. Utilization also provides information on how the distribution of people is during the day, thus, it is a good indicator to determine if the system has sufficient capacity to balance the flow of people.

Acknowledgments

This master thesis marks the end of my graduation project and concludes my master in Operations Management & Logistics at the Eindhoven University of Technology. It has been two years since I arrived in the Netherlands looking for new challenges and with the purpose to develop myself internationally. I have met extraordinary people so far and I would like to thank some of them who contribute in this master thesis and who supported me along the process.

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Ricardo García Castañeda

Contents

1 Introduction

1.1 Overview

Water is one of the most valued resources in Earth. The human dependence on it is essential to survive and it is vital for good quality services in sanitation and human health. Governments and organizations face enormous challenges to satisfy the actual water demand and have been working constantly to improve water services around the world; nevertheless, the reality is that current networks are insufficient to provide access to clean water to all the people. As the population increases, an increased demand for resources and food is required. This problem added to a growing scarcity of freshwater is now a major impediment to provide water stability in many parts of the world.

Access to water for life is a basic human need and the United Nations has listed "Water and sanitation" as one of the human rights for all the population (UNDP, 2006). Yet, it is estimated that there are more than 1 billion people that do not have access to safe drinking water and there are 2.6 billion people worldwide who do not have access to minimal level of sanitation according to the Human Development Report 2006. The population living in developing countries is the most prone to this problem since they do not have the infrastructure needed to have a proper quality system or the financial support required to build new facilities or water systems. Some people in developing markets are living in informal or illegal settlements acquired through the years. Consequently, governments and landlords claim they do not need to provide or invest in any services. Poor communities struggle every day to obtain water; the water facilities are sometimes far from their houses so they have to walk long distances and wait several hours to obtain water, they have to deal with poor water quality that affects their health, and in most of the cases, they pay some of the highest prices for water in the world. Every year approximately 1.8 million children die as a result of diarrhea and other diseases caused by unclean water and poor sanitation. Moreover, the deficits in water and sanitation undermine productivity and economic growth, reinforcing deep inequalities in the population and trapping vulnerable communities in cycles of poverty (UNDP, 2006).

Taking into account this problematic, HumanNeeds Project (HNP) and Procter & Gamble (P&G) made a collaborative project to improve the situation concerning the lack of clean drinking water and sanitation, and to contribute with the development of the community in one of the largest slums of Africa: Kibera, Kenya. HumanNeeds Project (HNP) is an american NGO working to provide clean drinking water to families in urban slum areas, while also providing access to knowledge, skill-sets and basic services. On the other side, Procter & Gamble (P&G) is an american multinational consumer goods company and the project is part of P&G's Sustainability Program based on the company's commitment to "making every day better for people and the planet through how we innovate and how we act". The company involvement is to create awareness about the challenges in low income markets and to identify opportunities. Also, P&G saw the opportunity to partner with HNP to introduce a laundry room into the Town Center. Through this partnership, P&G and HNP collaborate with the aim of providing access to clean drinking water, sanitation and an improved and resource efficient laundry experience, while empowering and developing the community.

The purpose of this project was to analyze the operations of the water center, build a model that represents the queues in a stationary standard approach, and use a simulation model to understand the flow of people during the day and how it creates queues in the system. Based on this analysis solutions were given to improve the service and prevent queues in the center.

In the first chapter, some background information is given about Kibera, the situation of water and sanitation in slums, and a description of the Town Center. Then, the research approach is explained with the research questions and the methodology. Subsequently, the analysis of the water system is made by creating an analytical and a simulation model. Estimations such as demand, arrival times, and service times were obtained to make the analysis and a comparison between both models is given. Afterwards, some sensitivity analysis was performed and possible improvements for water system are given. Finally, conclusions and contributions are discussed regarding the operations of a water center.

1.2 Kibera, Kenya

According to the Joint Monitoring Programme's 2012 report, there is still an unmet need in rural and urban areas for both water and sanitation. Access to safe water supply in Kenya is 59% and access to improved sanitation is 32%. Kenya has a limited renewable water supply and is classified as a water scarce country, suffering from constant droughts and water shortages. Urban migration also contributes to challenges in sanitation, as people crowd into cities and urban growth is unregulated.

Due to lack of access to water and sanitation, diarrhea is second to pneumonia in deaths in children less than five years of age, killing more young children than AIDS, malaria and measles combined. Water, sanitation and hygiene related illnesses are the number one cause of hospitalization in children under age five (UNICEF/WHO, 2009). Therefore, the importance of a reliable clean and safe water supply has a tremendous effect on the health and lives of people. Additionally, access to water and sanitation contribute to time savings for the population, more hours in school for children, and fewer health diseases and costs.

Kibera, located in the suburbs of Nairobi, is one of the biggest slums in Africa with a population of approximately 300,000 people living under unfavorable conditions. No census has been carried out; hence, estimates vary between 250,000 people to one million living in a surface of 2.38 km^2 (Desgroppes & Taupin, 2011). It is characterized by high population density, poor-quality housing, lack of adequate living space, and lack of basic infrastructure services like water, sanitation, solid waste management, roads, and electricity (Schouten & Mathenge, 2010). The slum is an informal settlement since the residents have settled illegally on the government land, which is one of the reasons why the government does not invest properly in Kibera.

1.2.1 Small-scale providers

Water supply in informal settlements is highly unreliable and just small areas have access to pipeline water, forcing people to seek alternative forms of provision. Unreliability is a direct result of poor infrastructure, rationing by the public water company and water shortages. In the absence of pipeline water, people have to buy water from a wide range of small-scale providers whose services are vital even if they provide services at high prices and poor quality. These water providers compensate the limited financial and human resources of the public sector and play three basic roles in the community. First, they act as gap fillers by raising the coverage levels, even if they lack of quality. Second, they extend water access to areas where there is no system of delivery and no infrastructure. Third, small-scale providers act as sub-concessionaires buying from the water company and reselling to customers (Kariuki & Schwarz, 2005). People in Kibera often utilize more than one regular source of water, switching between public standpipes, unprotected wells and water vendors depending on the water availability, distance to the source and waiting time to fetch their jerry cans. In the slums of Nairobi, Kenya, over 80% of the population relies on sources other than household/pipeline connections, including kiosks, water vendors and other small-scale providers (Gulyani & Talukdar, 2008).

Time spent on collecting water varies between each area and it is a common problem for habitants in slums. People have to choose their water sources by evaluating water quality, waiting times, distance to the source, price and unreliable systems among other variables. Sanitation is often inexistent and people do not have the facilities and infrastructure required to fulfill their needs. In Kibera poor households spend 45-55 minutes on average collecting water every day while the non-poor spend only 18 minutes, and that is excluding the time spent walking to the source and coming back home (Brocklehurst, 2005). Nevertheless, when water shortages are present the queues can be up to 2-4 hours and people do not have any other alternatives.

Contrary to the people belief, the poorest people pay more for water than the wealthy people who have access to piped water which has the lowest tariff per unit of water (Dagdeviren & Robertson, 2011). The prices charged to people living in slums are outrageously high, because of lack of economies of scale, intermediaries such as water vendors, and the transportation and distribution costs of the small water carried.

According to Hailu et al. (2011), the water distribution in developing markets is done in two different ways: fixed point resale business and mobile delivery services. Fixed point resale business consists on well water vendors, tap water vendors and water kiosks; while, mobile delivery services offered by pushcart vendors and tanker trucks.

Fixed point resale business

Tap water vendors and water kiosks

The services offered by the tap water vendors and water kiosks are very similar. Tap water vendors are private entrepreneurs relying on a single piped connection, usually selling water from their dwellings to the community. These vendors are unregulated and consist mainly of landlords supplying tenants, sometimes through a small piped network.

Alternatively, water kiosks are distributed across the community and often have more infrastructure (number of taps, holding tanks, often higher pressure). Some owners have between 3 – 5 water kiosks in Kibera that operate at least six days a week. Kiosks can usually serve more than one customer at a time from two or more taps, thus, speeding up the service rate. All these attributes contribute to the ability of water kiosks to sell more water than tap water vendors. Tap vendors sell on average 94 20-liter jerry cans of water a day; while the kiosks, on average, sell 238 jerry cans.

Most fixed vendors depend on the reliability of supply from the water company. They complain of supply disruptions caused by rationing from the water company. Some water points have water shortages 2 days a week but in some situations the water company cuts the water supply from Thursday to Tuesdays, so some water points have only 2 days of water supply. This affects the demand and the queues in several water points. The water rationing by the water company is a random process that affects some water points in the area. Therefore, the demand is always shifting from one water point to another depending on where they can find water. Water kiosk operators also complain of weak water pressure and its negative impact on the service rate and the time spent in line by consumers. Most fixed-point vendors operate between 12 and 15.5 hours a day, six or seven days a week. This schedule is interrupted when pipes run dry as a result of rationing by the water company (Hailu et al., 2011). Water delivered with these methods does not go into any quality check at the point of sale affecting directly the health of the consumers since it is assumed the water company is responsible of treating the water. Moreover, water pipes enter and are distributed in Kibera through unfavorable conditions such as open-air pipes, waste, and blackwater streams. Maintenance to pipes is not common, thus, many of them present leakages and the problem is that water is exposed to contaminants that enter the pipes and pollute the water that is sold to the community. People often boil the water before drinking it but the reality is that the water is not clean and safe to drink.

Well water vendors

Wells comprise an essential water source for households not connected to the water company's network. However, there are not a lot of well water vendors in Kibera since the installation costs can be elevated. Well construction is expensive and involves sunk costs associated with digging and construction, as well as the purchase of pumps and storage tanks. Before construction can begin, an official authorization is required. Concerns over water quality and quantity are decisive factors in the regulator's decisions to authorize well construction. Quality is also an issue in these centers. Normally, quality testing is carried out only at the time of licensing, with no subsequent monitoring. This has serious implications for the quality of the water distributed.

In contrast to the fixed-point vendors discussed above, who are dependent on a reliable supply provided by the water company's piped network, well vendors are better positioned to take advantage of negative water supply shocks in the network. Nevertheless, well supply also suffers from supply disruptions, caused by power outages (Hailu et al., 2011).

Mobile Delivery Services

Pushcart vendors

Operators of manual pushcarts obtain water mostly from wells, water kiosks or through an illegal connection to the piped network. They resell water to end users in 20-liter jerry cans. The initial investment cost consists of buying 15 to 30 jerry can containers at Kshs 200 per unit, and acquiring the pushcart (about Kshs 5,000) or renting it.

The competitive advantage of mobile vendors lies primarily in their ability to reduce the time cost for people associated with obtaining water by offering door-to-door vending. These vendors also play a larger role where kiosks and tap vendors either are absent or are too few to provide an adequate supply of water. About 64% of pushcart vendors serve households located far from any fixed-point water source. They may either walk house to house offering services or, more efficiently, deliver in response to mobile phone orders. Some vendors also have a number of regular customers, who receive a daily supply and therefore may qualify for a lower rate. A single mobile vendor serves, on average, 16 customers per day (Hailu et al., 2011).

Tanker trucks

Privately operated tanker trucks supply water in bulk to end users who can afford storage tanks. Tanker trucks obtain water either from private wells or directly from the water company. However, this is not common in Kibera since there are no roads and there is no infrastructure available for a truck to go around the community. They do so in response to mobile phone calls, covering all of Nairobi. Some tanker trucks operate 24 hours a day.

The business is typically operated as a family business. Some vendors purchase their own truck, while others rent a vehicle from the Nairobi City Council (NCC). All tanker truck operators require a business permit, issued by NCC for a fee. Truck operators incur recurrent costs associated with truck maintenance, parking fees, and operational equipment such as gloves, piping and pumps. Some government officials allege that the truck operators are sometimes involved in disrupting the piped supply network in order to boost demand (Hailu et al., 2011).

1.3 The Town Center

The Town Center is an infrastructure facility located in Kibera, Kenya that uses its own clean source of water from a borehole dug at 281 meters to provide several services concerning water and sanitation among others to the community. This center provides basic services such as a clean and safe drinking water kiosk, toilets, showers, and laundry.

Moreover, the center gives the slum some empowerment services like business skills training, micro-credit, WiFi cafe, health kiosk, and green marketplace in order to help the development of the community. These integrated services provide a holistic solution to the challenges of living in a slum and together, they can help people with a road map to creating a better life.

1.3.1 Water system

Water is the core of the Town center and the quality is really important in order to provide a good service to residents in Kibera. To assure the quality of the water system, the system is monitored closely and continuously with the support of the University of Nairobi. The water system is divided in two subsystems: one for the potable water operations and another one for non-potable water operations, both consisting of several processes.

For the potable water system, first, the water is obtained from the well with a capacity of 20,000L per hour. To make the water potable, it goes through an Alumina Fluoride treatment system to control the fluoride in the water, to regulate the pH and to add a small amount of chlorine needed to preserve a good quality in water until the residents make use of it. After this, the water is distributed to the Town Center services such as water kiosk, laundry, toilets, and showers.

The non-potable water system is the second phase of the water operations and consists of treating and recycling the water that has been used in the Town Center (café, cleaning, laundry, showers, and toilets). All the water used is collected in a Septic tank and then it goes through the Anaerobic filter tanks and Horizontal roughing filters to remove the solids in the water. After that, the water passes through the Flow equalization tank, Trickling filters and Upflow roughing filters. Finally, it goes through the Slow sand filters and the Chlorine bath system before it reaches a Recycled water storage tank with a capacity of 60,000 L. One portion of the recycled water will be used for the toilets in the Town Center, while the rest will be distributed outside the center in a school with 3,400 students for irrigation purposes and toilets.

2 Research approach

2.1 Research questions

Nauges and Whittington (2009) explain that there is a lack of attention and research papers in developing settlements since the conditions surrounding water access often vary across households, and this variability makes it almost impossible to base a comprehensive analysis of household water demand on secondary data from the water utility. Moreover, households often rely on a variety of water sources, including piped and non-piped sources with different characteristics and levels of services (price, distance to the source, quality, and reliability, between others). For many households in developing countries water is a heterogeneous good, which is not usually the case in industrialized countries (Mu et al., 1990). Households have access to and may use more than one of several types of water sources, such as water kiosks, public or private wells, public or private taps, water vendors or resellers, tank trucks, water provided by neighbors, rainwater collection, or water collected from rivers, streams, or lakes (Nauges & Whittington, 2009).

There are just few models in the literature referring to operations in water systems and most of these studies refer to smaller water points with less infrastructure and number of services than the Town Center. A groundwater management model is presented by Batabyal (1995) applying queuing theory (M/M/1 queue and M/G/1 both with finite capacity). The model is looking to maximize the profit between the sale of water and the cost incurred from the provision and use of groundwater. The uncertain demand for water over time is modeled by an independent and identically distributed stochastic arrival process of water users, while, the uncertain supply of water is modeled by an independent and identically distributed stochastic supply process of the water manager. The stochastic processes are independent of each other and there is only a single manager in charge of dispensing groundwater from an aquifer to the different users who pay a fee for the water they receive. The article also present how the manager could choose a quota on water allocation and the rate at which he would supply water in a certain time period so as to maximize the residual benefit arising from the provision and use of groundwater.

Another model based on the process and the design of a water supply system itself is acknowledged by Sharma et al. (2004). The design of a water supply system is aimed to meet the needs of the population for a specific period in future. The future population and the amount of water required by the people must be estimated keeping in view the industrial and commercial growth of the area. In this paper dynamic programming is used to find out the optimal number of facilities required and the optimal installation times of such facilities in a given time period. The model consists of a dynamic programming that has been used to minimize a performance index based on the waiting cost of the population needing water supply, and cost of unutilized capacity. These two costs will ensure the proper size of the water system and if additional facilities need to be installed at a particular time in the future.

The amount of limitations involved while improving water systems in developing countries is high as a result of lack of infrastructure and unreliable systems. People in these settlements have a heterogeneous behavior since they have different small scale providers to obtain water from and water shortages can occur often affecting the forecast and data available of each water point. Therefore, information and data available is scarce and difficult to obtain. Furthermore, there is a lack of models that evaluate water systems in developing countries and their operations in order to improve the service given to communities.

The primary contribution of this project was to analyze the behavior of the water system, to give possible solutions to improve the service, and to help create a business plan with reliable information by understanding the operations in the Town Center. In order to develop the project in the correct direction, some research questions were addressed:

- ☐ *What data is required to understand the water system?*
    - *What is the demand of the town center?*
    - *What is the distribution of service times?*

- ☐ *How are the operations in the water center?*
    - *What is the congestion of the system?*
    - *How often are queues formed?*
    - *What are the bottlenecks of the water system?*

- ☐ *How is the performance of a standard stationary model in a dynamic environment such as the Town center?*

- ☐ *What improvements can be made to the system?*
    - *Are they feasible?*

2.2 Methodology

The purpose of this master thesis was to provide significant information to improve the service given to customers by building models (standard queuing model and simulation model) that are capable of evaluating congestion and queuing in each service (water kiosk, toilets, showers, and laundry). The demand was estimated and service times were measured in order to analyze the water system. Several solutions were presented to improve the service in water systems and they were simulated to check the feasibility in case of possible changes in the system.

The methodology will be based in several stages described below:

- *Capacity of the water system* – Based on the system infrastructure and characteristics, the Town Center capacity was checked. The process was revised to detect possible issues regarding the flow of water and possible bottlenecks during the start-up phase.

- *Demand estimation* – The purpose of this stage was to have a better understanding of the demand and its behavior. At the beginning the intention was to measure the demand once the center started operations. Nevertheless, the construction of the Town Center was delayed and the approach taken was to estimate the demand.

- *Process modeling* – In this phase, the actual utilization was obtained, bottlenecks and critical stations were detected, and queues in each service (water kiosk, toilets, showers, and laundry) were evaluated. Also, the number of people served and the service times involved in the system were considered. The process modeling phase consisted of two parts: standard queuing model and simulation model. In particular, the main goal was to check the distribution and obtain the formulas capable of analyzing the system and to calculate in each process: the queuing times, number of people waiting, number of people served, and utilization. The system was based on a queuing network in which, according to the Kendall's Classification, the demand and service times presented a General Distribution in most of the processes, thus, the coefficients of variation needed to be calculated in order to evaluate the system in a G/G/m queuing model. In the second phase of Process modeling, a simulation model was done with the Arena simulation software using different demand distributions based on the pattern of the day to analyze the system and compare it with the standard queuing model.

- *Evaluate the standard stationary model in a dynamic situation* – In this part, a comparison was made in order to analyze the behavior of the standard stationary model against the simulation that takes into account a dynamic environment.

- *Sensitivity analysis* – A sensitivity analysis was made assuming changes in the system. This part is important because it assumes modifications in the water system in key elements that can change the expected results. Therefore, to understand in a better way the water system several scenarios were considered.

- *Possible solutions* – Several solutions were created to improve the service given to consumers and to reduce queues. The solutions presented were simulated to evaluate their performance and to observe the improvements that can be obtained in the water system.

- *Feasibility in possible solutions* – An evaluation of the solutions will be made taking into account the feasibility in order to determine what would be the best option for the Town Center.

3 Water system analysis

In this chapter an analysis of the water system is done. First, a description of the facilities and service stations is given. Then, the methodology to obtain the estimations is explained and an analytical queuing model is built to perform the analysis. Finally, simulations are made to analyze different scenarios in the water system and a comparison is given between both models: analytical model and simulation model.

3.1 Capacity & Services

To have a clear understanding of the Town Center it is important to know the infrastructure of the center, its capabilities and the service stations that are analyzed. A description of the filtering and water treatment processes is given in the Appendix A.

3.1.1 Service Stations

The basic services of the Town Center are the services regarding water and sanitation. A short description and the number of units available are presented below:

Payment

People have to pay for the services to allow the center to be sustainable. The prices are fixed within the range of prices available in the market nowadays, becoming a reliable source of water and sanitation for local people in the community. The water center counts with two methods of payment: cash and top-up cards. There is a counter in the center available for cash and people will be also be able to top their cards up with a financial institution in the Town Center. Although top-up cards seem to be a good option to prevent queues in the payment station, it is assumed that people will struggle and would prefer putting small amounts of money in the card, thus, queues are not eliminated completely in this station. Mobile-phone based money transfer and micro financing services (M-Pesa) were considered since they are popular payment systems in Kenya but due to high transaction costs they were discarded. Moreover, cash payments should be avoided because the center is located in an area with high rate of criminality and it could be risky to manage a big amount of money. As a result, top-up cards will be implemented as an alternative payment process that can help us reduce queues.

Water Kiosk

The water kiosk is the most important station of the Town Center since it will have the greater flow of people and it is believed that it will account for approximately 40% of the revenue in the water center. People will arrive with jerry cans (20L) to fill them up with clean drinking water. The station will have in total 15 taps available to serve the community and it is expected to deliver with a service time of 60 seconds on average.

Laundry

On one hand, the laundry station is being composed with 7 hand washing stations where people will wash their clothes using buckets of water but they will count with new devices to clean in a more efficient way their clothes by using a washing board specially created to improve the washing experience. On the other hand, the laundry station will have 2 laundry machines including 2 dryers, reducing the washing and laundry time to half of the current process.

Toilets & Showers

Toilets and showers are merged inside the same station although they are divided by genre. The center will have 6 toilets for each genre. Regarding showers, the center will have 11 showers for men, while 13 showers will be for women. The center also has toilets for disable people and children (for small school nearby), although they are not taken into account for further analysis.

3.1.2 Performance measurements

HumanNeeds Project was not aware of the problematic of congestion and queues in the system. Also, there were not a lot of studies or previous articles about operations of water centers in slums. That is the reason why the Town Center was built without having clear indicators of which stations can be the bottlenecks and therefore, which services need more flexibility for possible modifications in the future. Performance measurements were not considered for the operations by the organization in the water system, thus, at the beginning the approach taken in this project was to analyze the system on how it works to detect risks and waiting times to give proper suggestions, recommendations and give performance measurements that can be used for the future operations.

3.2 Demand estimation

Analysis of demand for water in developing countries is complicated because households have access to and may use more than one of several types of unreliable water sources, such as water kiosks, public or private wells, public or private taps, water vendors or resellers, tank trucks, water provided by neighbors, rainwater collection, or water collected from rivers, streams, or lakes (Nauges & Whittington, 2009).

Due to the construction and start-up delay, the demand will be estimated. The approach taken was to define different market zones and calculate the amount of people living in each of them. Marketing team helped to define the zones involved, resulting in 3 different areas with radius of 200m, 400, and 600m from the Town Center (Figure 1 – HNP's Kibera market zones).

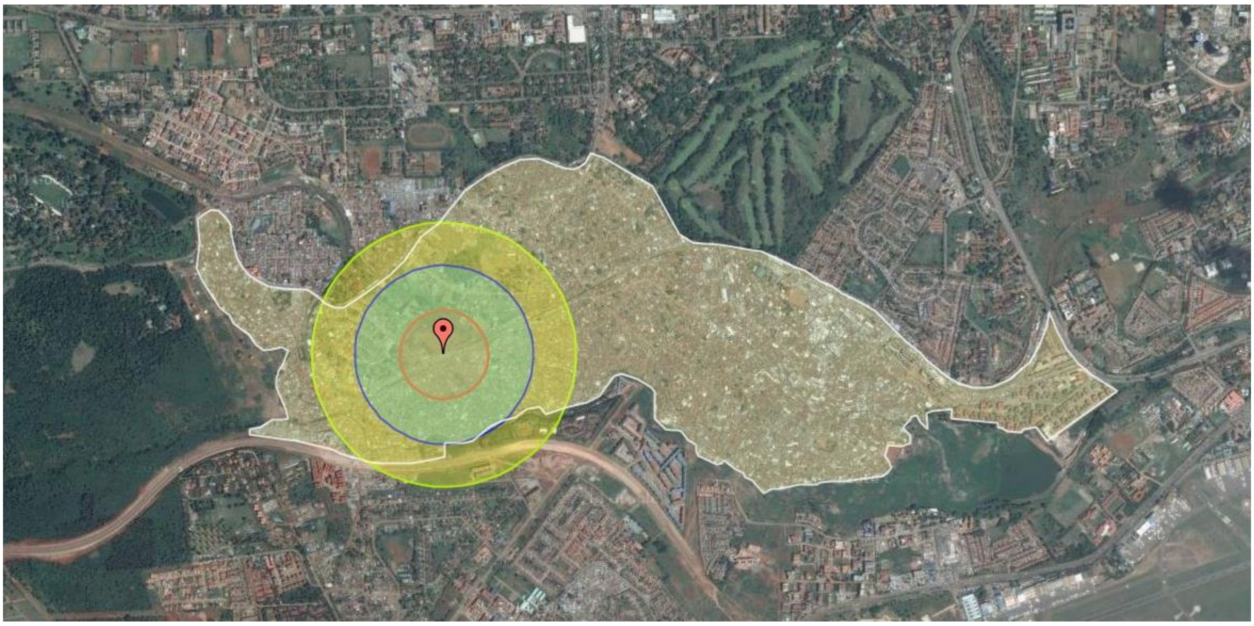


Figure 1 – HNP's Kibera market zones

Kibera itself is divided in 13 villages: Kianda, Soweto West, Raila, Gatwekera, Olympic, Kisumi Ndogo, Makina, Kamdi Muru, Mashimoni, Laini Saba, Lindi, Silanga, and Soweto East. Nevertheless, the Town Center expects to impact directly 6 of these villages as presented below in Figure 2 - Villages considered:

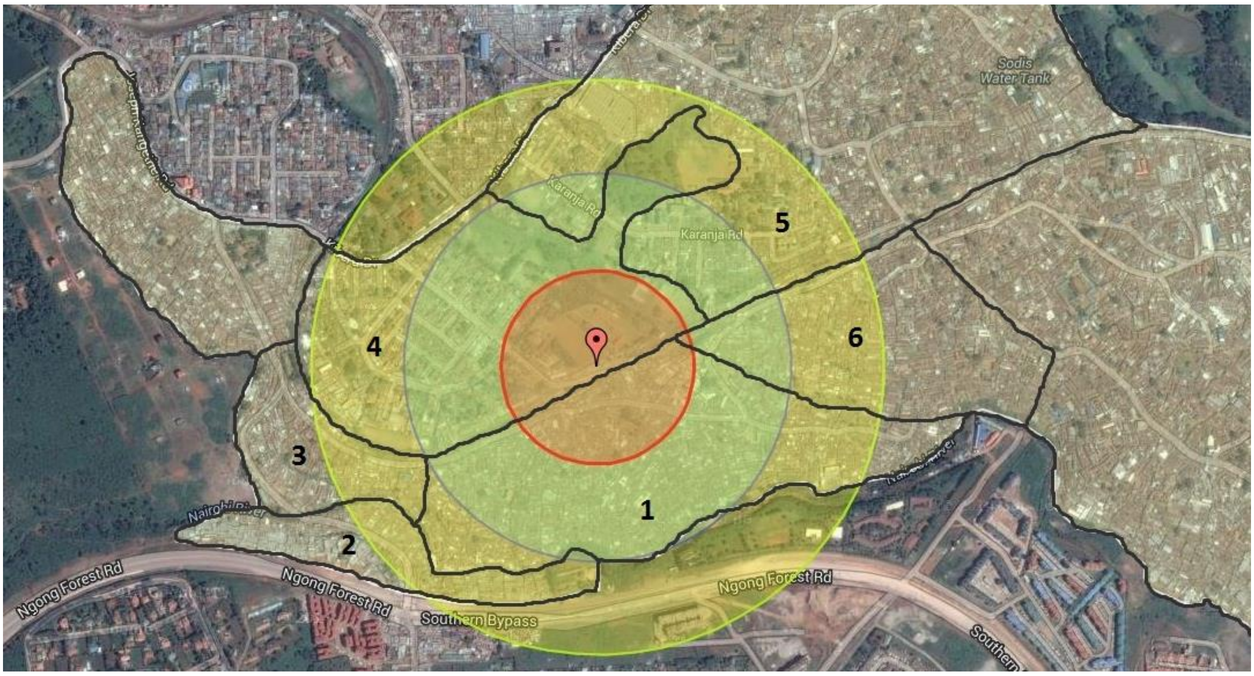


Figure 2 - Villages considered in the defined zones

1 – Gatwekera

2 – Raila

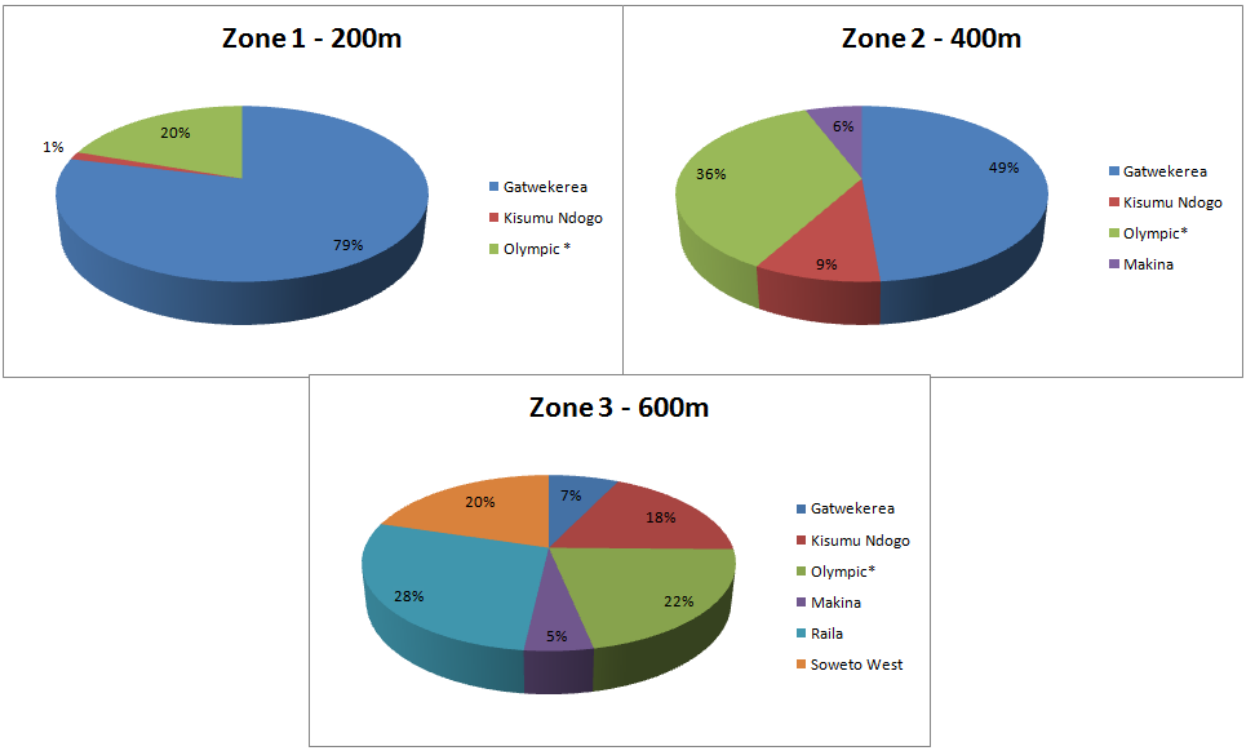
3 – Soweto West

4 – Olympic

5 – Makina

6 – Kisumi Ndogo

Each marked zone is formed with several villages, hence, it is important to consider them because each one of them has different population and the population density is also not the same. For a better demand estimation different villages in the marked areas were taken into account as shown in Chart 1 - Zone Composition:



* Olympic village has a greater extension but we only consider the habitable area

Chart 1 - Zone Composition per zone

To determine the population of each marked zone, a case study from KeyObs (2009) using high satellite imagery and sample field survey was used. This case study presents a detailed report of the population living in each village so the proportion inside the marked zones was calculated assuming that the population density is spread equally in every village (Table 1 - Population living per zones).

		POPULATION		
Village	**Population KeyObs**	**Zone 1**	**Zone 2**	**Zone 3**
Gatwekerea	23,053	4,327	12,866	4,454
Raila	6,644	0	0	3,099
Soweto West	10,360	0	0	3,948
Kisumu Ndogo	16,437	68	1,706	5,631
Olympic	12,000	678	4,656	4,464
Makina	31,602	0	2,192	2,481
TOTAL		5,073	21,419	24,077

Table 1 - Population living per zones

To determine the demand, a consumers' survey was conducted to measure the willingness of people to come to the center based on the marked zones. The survey was conducted by staff members in Kibera during one week. In the survey, people were asked about their water consumption habits in order to know when they go to water centers, how many times per week, how many jerry cans do they buy, how many people consume those jerry cans, and their willingness to go to the Town Center, between other questions. A total of 150 interviews were conducted, 50 on each zone (Zone1 = 200m radius, Zone2 = 400m radius, Zone3 = 600m radius) to define the number of people on each zone that could potentially be interested on using the services in the Town Center.

Based on the consumer's survey, the percentage of people and potential consumers that are willing to come from different zones (A: 0-200 meters; B: 200-400 meters; C: 400-600 meters) were obtained as shown in Table 2.

Zones	**Distance**	**Willigness of people to come to the Town Center**
Region 1 =	200 m	56%
Region 2 =	400 m	30%
Region 3 =	600 m	22%

Table 2 - Willingness of people to come to the Town Center

Moreover, the average water consumption per person was determined to be 1.073 jerry cans per day (21.46 Liters) with the survey and compared with some literature studies that range the water consumption between 0.8 and 1.12 jerry cans per day (Macharia, 1992; UN-HABITAT, 1997; Aquaclean Services, 2010). Taking into account the willingness of people and the water consumption of the survey and the literature, a demand of approximately 1,750 consumers per day for the water kiosk was fixed, estimating the jerry cans consumption to be around 10,000 per day. This is considering that consumers buy on average 5.8 JC per visit based on the survey represented in Chart 2. Women and children are normally the people in charge to collect the water (Bell et al., 2010; UNDP, 2006; Hailu et al., 2011). Women go to water points with their children in order to collect the water for everyone in their house as it can be seen in the Appendix B. Normally, people use straps in their heads to carry more jerry cans per visit and they encourage children to do this labor to reduce the number of visits to the water centers since queues can be a problem.

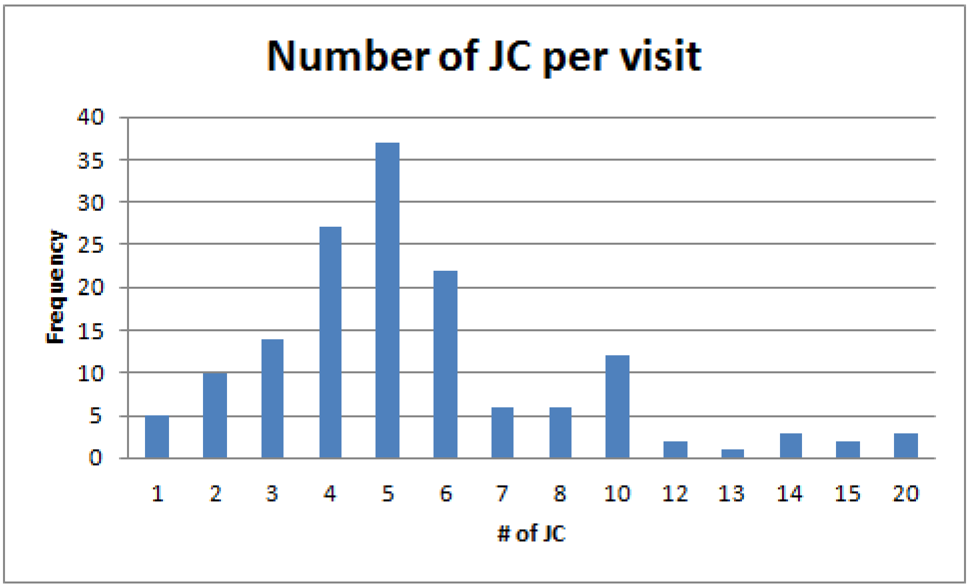


Chart 2 - Number of JC people buy per visit

According to the consumer's survey, it is expected that 10% of the demand will consist on water vendors that buy 10 or more jerry cans per visit. Water vendors use reliable water centers to fill jerry cans and then they resell them at a higher price in the community. They have pushcarts to walk inside Kibera and where they can transport more than 10 jerry cans per trip. The rest of the demand is expected to be distributed normally with the following parameters: 4.58 mean and 1.61 of standard deviation. Moreover, at least 50% of the population will make use of the facilities in the morning before work (5:00am – 11:00am), 30% in the evening (4:00pm – 9:00pm), and 20% in the afternoon (11:00am - 4:00pm). This people are households that buy water almost every day to supply water to their families.

3.3 Analytical queuing model

3.3.1 Analytical Queuing Model – G/G/1

The water system was analyzed in a standard stationary state in order to build an analytical queuing model. The water system presents different demands (arrival rates) depending on the time of the day. The demand is changing continuously, thus for the steady state approach, the period considered was when the process suffered more congestion. This time interval is when the water center has more arrivals during peak-hours. Peak-hours are common and constant during the week because they occur before people go to work in the morning and after they come back from work.

To represent in a queuing model the Town Center, some considerations were made taking into account a G/G/1 queuing system. It is considered that the inter-arrival times and service times are according to general distributions because in the M/M/1 model commonly used, the arrival and service times are assumed to be Markov (memoryless) and the variability that is present in real life cannot be modified. People will arrive and it will be served with a FCFS (First Come First Served) approach.

Since the models become complex without non-exponential data it is not possible to obtain exact expressions for the various performance measures. However, some approximations have been reviewed in the past (Ravindran, 2008). For the present model the approach used by the Kingman's equation will be taken into account for being accurate and adaptable to different types of distributions. The formula itself is an approximation which depends on utilization, variability, and service time. In this type of model the variability of the arrival rates and/or the service times can be changed, meaning that service times and arrivals can take on any probability distribution, as long as they are independent of one another (Hopp, 2008).

To represent the variability in the system, the coefficients of variation (CV) of inter-arrival times and service times were defined as:

$$c_a = \frac{\sigma_a}{\tau_a} \qquad\qquad c_s = \frac{\sigma_s}{\tau_s}$$

Where:

$\sigma_a =$ represents the standard deviation of the interarrival times

$\tau_a =$ represents the mean time between arrivals ($arrival\ rate\ =\ \lambda\ =\ 1/\ \tau_a$) service time

$\sigma_s =$ represents the standard deviation of the service time

$\tau_s =$ represents the mean service time ($\tau_s\ =\ 1/\mu$)

Therefore, to calculate the Waiting time in the queue, the Kingsman's equation was used:

$$W_q{}^{G/G/1} \approx \left(\frac{{c_a}^2 + {c_s}^2}{2}\right)\left(\frac{\rho}{1-\rho}\right)\tau$$

The total time a user spends in the system is represented by:

$$W^{G/G/1} \approx \left(\frac{c_a{}^2 + c_s{}^2}{2}\right)\left(\frac{\rho}{1-\rho}\right)\tau + \tau$$

3.3.2 Service Stations, Multiple servers – G/G/m

The queuing model for the Town Center is based on a G/G/1 queuing system explained before in each service station. Nevertheless, each station has multiple servers depending on the service facility and the model should be represented in a G/G/m queuing model where *m* represents the number of servers on each station. As stated before this model considers the arrival times and service times to be general distributions. With this model the coefficients of variation were used to represent the variability that is present in the system.

$$W_q{}^{G/G/m} \approx \left(\frac{c_a{}^2 + c_s{}^2}{2}\right)\left(\frac{\rho^{\sqrt{2(m+1)}-1}}{m(1-\rho)}\right)\tau = \left(\frac{c_a{}^2 + c_s{}^2}{2}\right)W_q{}^{M/M/m}$$

3.3.3 Queuing Networks

The Town Center is not just a single station facility; it is a set of interconnected stations and queuing systems that is commonly called Queuing networks. Customers move to another station for additional services or leave after they finish their services at a predetermined station. The water system is a flow of processes of different services that intend to give basic services like water and sanitation to one of the biggest slums in Africa.

The queuing network is represented on Figure 3 - Town Center's Queuing Network. The arrivals consist of 8 different demands that represent each service:

- **JerryCans (JC) Lifelink** – This people represent the percentage of the demand that will use the water kiosk with the Lifelink station. Lifelink station is a machine that will be able to receive payments and dispatch water automatically without the presence of a staff member. The Town Center is considering one machine that allows water supply for 24 hours a day in case people need water during the night.

- **JerryCans** – This percentage of the demand is considering people that will arrive to fill up their jerry cans using normal taps.
- **Laundry_Machine** – The demand will consist on people that use the laundry station with 2 washing machines and dryers that are available at the laundry station.
- **Laundry_Hand** – People arriving will be using 7 hand washing stations that provide the resources to facilitate washing clothes by hand.
- **Toilets M** – This people will be using the toilets for men (6 units).
- **Toilets W** – This percentage of the demand will be using the toilets for women (6 units).
- **Showers M** – People arriving will use 11 showers that are available at the showers/toilets station for men.
- **Showers W** – This percentage of the demand will be using 13 showers at the showers/toilets station for women.

After the arrivals, those demands will merge in the payment process before receiving each service. JerryCans (JC) Lifelink demand do not need to go through the payment process since the Lifelink station has its own payment system. Once the payment is done, people will proceed to 3 different services mainly:

- Water Kiosk – Consisting of the Lifelink station and the water sales station with 15 taps. People arriving into the Water Kiosk rarely arrive with a single JerryCan.
- Laundry – This service is divided between the washing machines and the hand washing currently used in Kibera.
- Showers/Toilets – Showers and toilets are merged in the same facility. The only difference is that there are divided by genre. Each genre has its own facility consisting of toilets and showers.

After the services, people leave the system. In the analytical model, the queuing system only allows one service per person; nevertheless, in the simulation phase it is possible to simulate several services per person.

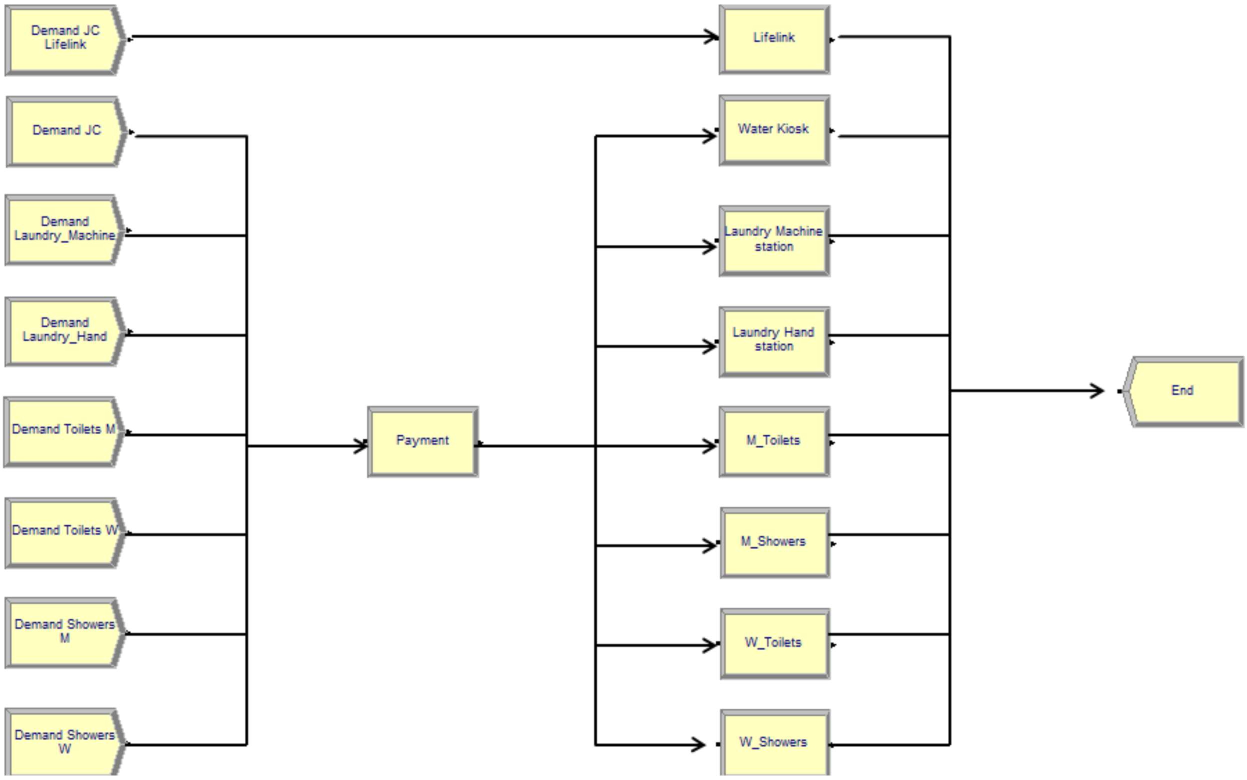


Figure 3 - Town Center's Queuing Network

In a queuing network, each process has a relation with the following processes, meaning that the departures from one station are arrivals to another station. Therefore, by flow of conservation, the departure rate is equal to the arrival rate, so the mean of the interdeparture times equals the mean interarrival time. Kuehn (1979) presented a simple approximation for the squared coefficient of variation of the interdeparture time for G/G/1:

$$c_d{}^2 \approx (1-\rho^2)c_a{}^2 + \rho^2 c_s{}^2$$

Nevertheless, for a G/G/c model the formula results as:

$$c_d{}^2 \approx (1-\rho^2)c_a{}^2 + \rho^2 \frac{c_s{}^2 + \sqrt{m} - 1}{\sqrt{m}}$$

This approximation permits the coefficient of variation of the interdeparture time to adapt to every situation. Under light conditions (ρ close to 0), $c_d{}^2$ is approximately equal to $c_a{}^2$, while under heavy load conditions (ρ close to 1), it is approximately equal to $c_s{}^2$ in the G/G/1 model and to $\frac{c_s{}^2+\sqrt{m}-1}{\sqrt{m}}$ in the G/G/m queuing model.

3.4 Analysis

3.4.1 Estimations

The Town Center had a delay in the construction due to some financial difficulties. The initial purpose was to measure the demand and the service times during the start-up phase of the center. Nevertheless, the start-up phase got delayed a couple of months and to obtain the information needed for the analysis some research in the area was made.

To define the time interval of study, the peak-hours were identified. Considering the results from the demand estimation survey, it was known that at least 50% of the population goes to water points in the morning before going to work, 20% in the afternoon, and 30% in the evening. Thus, congestion is at its most during early hours of the day and considering this period of time, measurements for the arrival times and service times were taken.

To obtain the information needed for Arrival and Service Times a research regarding several water points in Kibera was made. Two different methodologies were created to take the measurements needed for the times. For the Arrival times a water center with multiple services was selected. The measurements were made non-stop during the peak-hours taking into account the exact time a person enters a water point (before he starts any service or before queues). For the Service Times, the measurements of times were taken when people enter the service (toilet or shower) until they go out of the center. For the Water kiosk, measurements were done in a water center where the average filling time is 60 seconds because that is the expected time the taps of the Town Center will have.

For the Service Times, 236 measurements were taken from water centers in the area for the water filling process (jerry cans of 20 liters), toilets, and showers. Every measurement was taken without considering queuing or waiting times; thus, the times consisted only in the time people spend by using each service. A Weibull distribution was created for the process of filling 20 liter jerry cans since it was the best distribution that fits the data (Table 3):

Function	Square Error
Weibull	0.00778
Exponential	0.00856
Erlang	0.00856
Gamma	0.00935
Beta	0.00953
Lognormal	0.0377
Normal	0.054
Triangular	0.0944
Uniform	0.202

Table 3 – Square Error: Water kiosk

To fill a single JerryCan a distribution was made (Chart 3) resulting in a Weibull distribution: 34+WEIB(32.1,1.42). This represents a service time of 62.9 seconds on average to fill a 20 liter JerryCan.

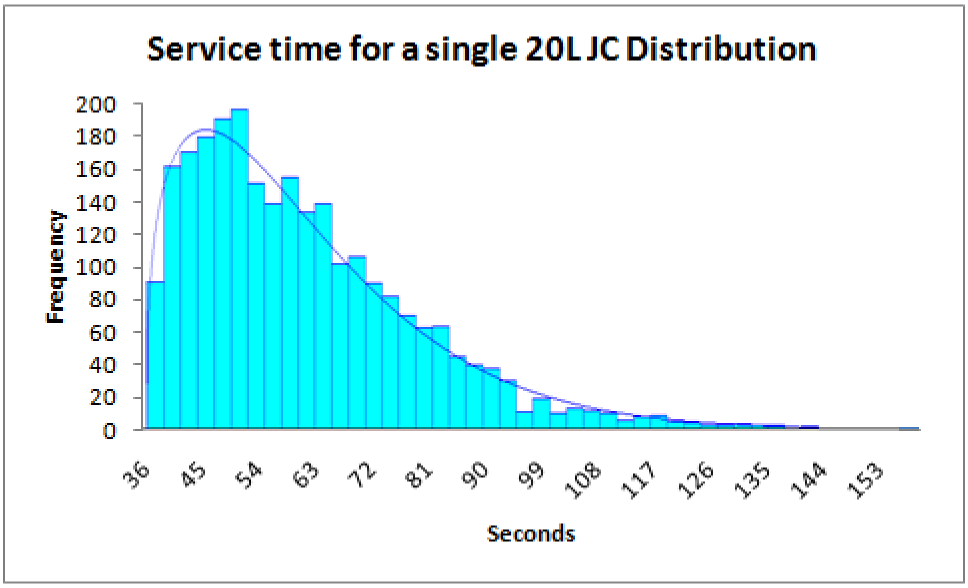


Chart 3 – Service Time: Single 20L JC Distribution

The Water Kiosk is a complex station because people buy multiple jerry cans per visit. Moreover, water vendors might go to the station and fill more than 10 jerry cans. Based on the number of JC per visit information that it was obtained in the demand estimation survey and this 20L JerryCan Distribution, a new distribution was created for the Water kiosk service times, resulting in a Lognormal distribution (Chart 4) with parameters: on average 5.59 minutes and standard deviation of 3.62. This distribution represents the time a server is being used by a user that might have several jerry cans with him.

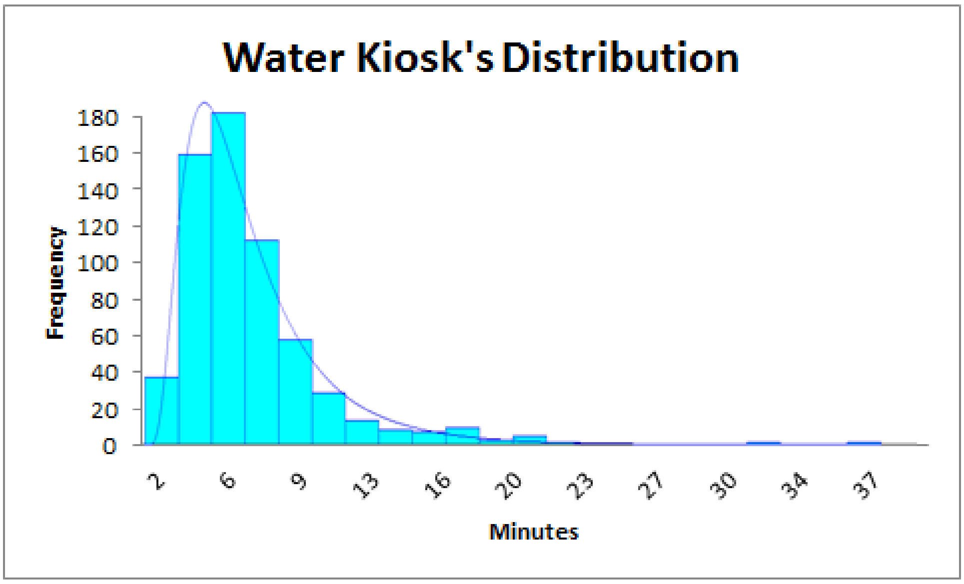


Chart 4 – Service time: Water Kiosk's Distribution

Around 200 measurements were taken for Toilets and Showers, and the same procedure was made for to evaluate which distribution fits best the data. For the Toilets' service times, the Weibull distribution (Table 4) was the best according to the lowest Square Error, while in the Showers' service times, the Exponential distribution (Table 5) was the most appropriated.

Function	Square Error
Weibull	0.0164
Beta	0.0171
Normal	0.0185
Gamma	0.0207
Triangular	0.021
Erlang	0.0264
Lognormal	0.0507
Uniform	0.0632
Exponential	0.069

Table 4 - Square Error: Toilets

Function	Square Error
Erlang	0.0126
Exponential	0.0126
Gamma	0.0221
Weibull	0.0307
Lognormal	0.0496
Beta	0.0536
Normal	0.0734
Triangular	0.134
Uniform	0.255

Table 5 - Square Error: Showers

Based on the previous information distributions for Showers and Toilets were created resulting in a Exponential distribution 306 + EXPO(82.5) for Showers (Chart 5) and a Weibull distribution 53 + WEIB(185, 1.8) for Toilets (Chart 6). This represents a service time of 6.5 minutes on average in the Showers and 3.6 minutes in the Toilets. These distributions are obtained with an input analyzer software. There are some lower bounds in the distributions meaning that based on the measurements the service time of the showers is never less than 5 minutes and the toilets are never use below 50 seconds.

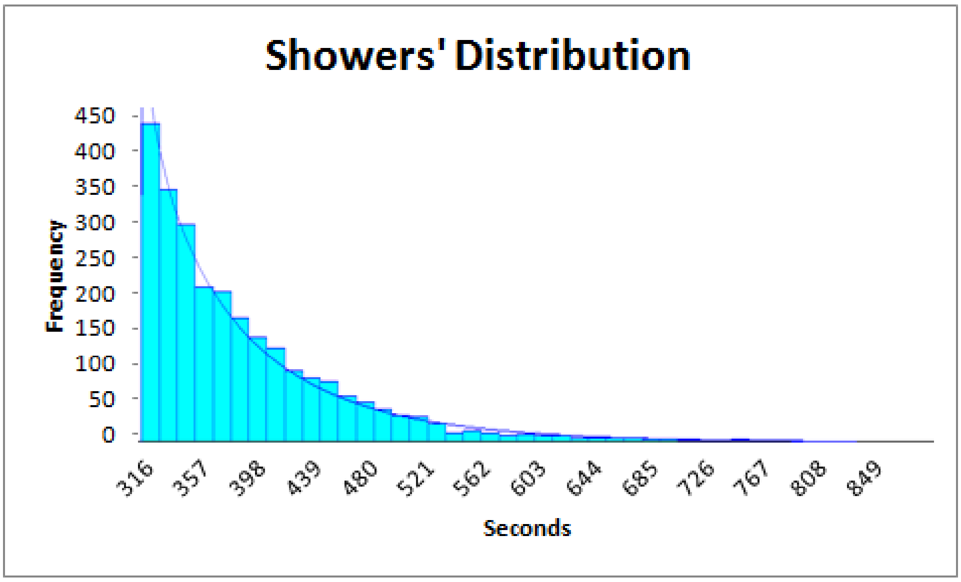


Chart 5 – Service time: Showers' Distribution

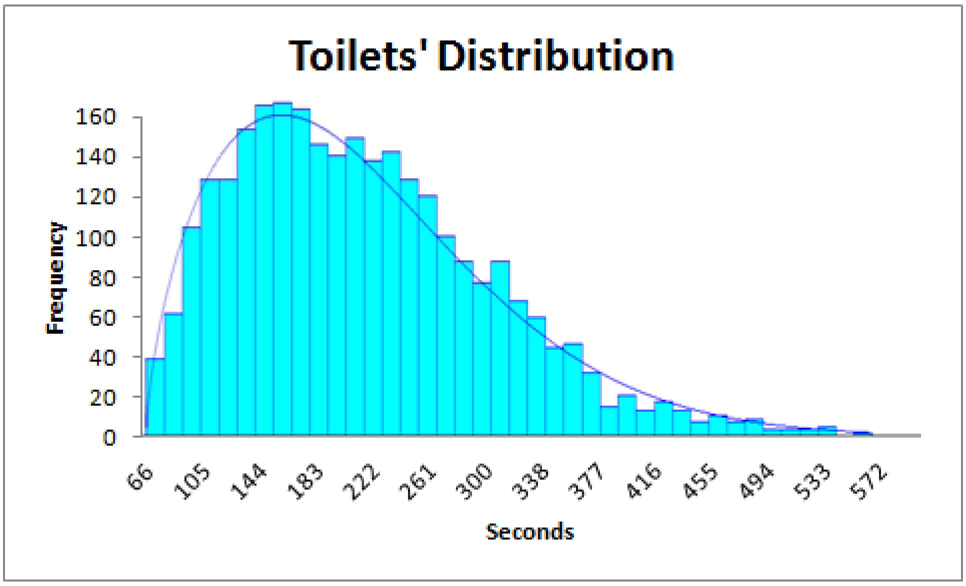
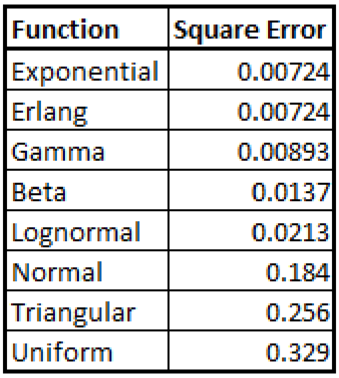


Chart 6 – Service time: Toilets' Distribution

The payment process regarding the top-up cards is still not defined in the Town Center. Nevertheless, the payment will be done with cash at the moment so the process will be faster than if people have to go to the Equity bank to top up their cards. It is assumed an exponential distribution with 32 seconds on average. No measurements were taken regarding the Laundry station (Machine/Hand wash) since a previous research by P&G was made regarding the washing characteristics of Kibera stating that people usually spend 2 hours doing laundry at their homes. A normal distribution was considered for both services with parameters of 120 minutes on average with 30 minutes of standard deviation for the Hand washing service and 60 minutes with 10 minutes of standard deviation for the Washing machines. The washing machine has an operational time of 45 minutes but the organization wants to consider 60 minutes as service time with a little deviation since the laundry machine time is fixed. For the Hand washing, the amount of water given will be around 100 liters of water, meaning that the amount of clothes is on average the same. Moreover, P&G is providing with special washing boards to reduce time people spend washing their clothes.

With the information about Service Times, the total capacity was calculated for laundry services, toilets and showers to obtain the demand per day. For these services the demand was calculated with the Marketing team based on the full capacity and considering that 80% of the time the laundry services have people and 75% of the time showers and toilets are serving the population. Water Kiosk demand was calculated as it is described before with different impact zones and surveys to know the willingness of people to go to the center (3.2 Demand estimation).

For the Arrival Times distribution, 100 measurements from 7:00am till 8:30am in a weekday were taken in a water center of Kibera with the same services as the Town Center (water sales, toilets, and showers) but with less capacity. Since there is no water center with the exact same characteristics or infrastructure in Kibera, it is assumed that the distribution has the same behavior as the water point consulted. The distribution found for the arrival times fits in a great manner the Exponential distribution since it was the one with the less square error as shown below (Table 6):



Function	Square Error
Exponential	0.00724
Erlang	0.00724
Gamma	0.00893
Beta	0.0137
Lognormal	0.0213
Normal	0.184
Triangular	0.256
Uniform	0.329

Table 6 - Square Error: Arrival Times

With this information regarding arrival times, a distribution for the Town Center based on the estimated demand was created (Chart 7) resulting in an exponential distribution with a rate of approximately 556 people during peak-hours. This represents a person arriving the water center on average every 6.48 seconds.

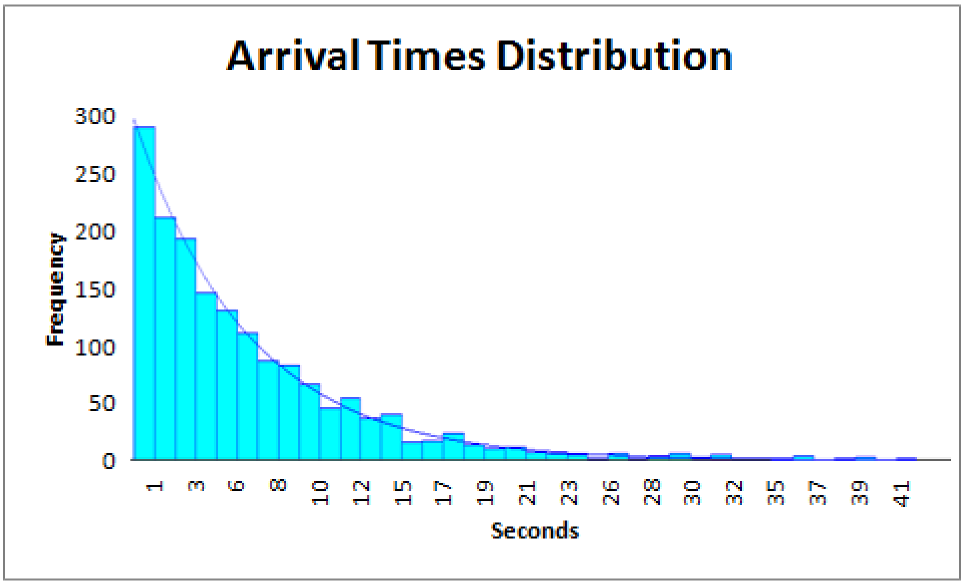


Chart 7 - Arrival Time: Distribution

On the analytical model the weekday peak-hours were considered since the system will operate most of the time in this scenario being a critical period because most of the people will arrive in the morning. Moreover, the model only considers single services per person. HumanNeeds Project has some financial problems so no big investments are planned at the beginning. Simulations assuming the weekend's scenario are presented in Chapter 5 with some sensitivity analysis to verify the situation.

3.4.2 Results of the analytical model

Considering the estimations presented previously the analysis was made for every service station in the water system using the analytical model. The results are presented below in Table 7:

		Time (W)		# of customers (L)	
	Utilization	Waiting (min)	Total Station (min)	Waiting	Total Station
Payment	98.77%	5.39	5.92	49.88	54.82
Water Kiosk	98.06%	12.63	18.22	33.23	47.94
Lifelink	94.40%	74.86	84.13	7.62	8.57
Shower M	92.70%	2.21	8.70	3.47	13.67
Shower W	92.70%	1.70	8.19	3.15	15.20
Toilet M	91.32%	1.88	5.53	2.82	8.30
Toilet W	91.32%	1.88	5.53	2.82	8.30
	Utilization	Waiting (hr)	Total Station (hr)	Waiting	Total Station
Hand wash	97.24%	3.31	5.14	12.37	19.17
Machine	95.64%	3.48	4.38	7.43	9.34

Table 7- Analytical model queuing results

The analysis during peak-hours shows that all the services have more than 90% of utilization, resulting in long queues in some cases. It is important to note that for the payment system an extra server (a total of 5 servers) was needed in order to maintain the system stable. The service station with the highest number of customers waiting is the payment system with approximately 50 people waiting, followed by the Water kiosk and the Hand wash in the Laundry station with 33 people and 12 people respectively.

The total cycle time of people in the system depending on the type of service they chose were obtained and are presented in Table 8:

	Total (min)
Payment	5.92
Water Kiosk	24.14
Lifelink	90.05
Shower M	14.62
Shower W	14.11
Toilet M	11.45
Toilet W	11.45
	Total (hr)
Hand wash	5.23
Machine	4.48

Table 8 - Total cycle times in analytical model

The service that has the greatest time overall is the Hand wash in the Laundry station with a total of 5 hours 13 minutes. The Service time takes two hours on average but 63% of the time (3.31 hr) people spend it waiting in queues. For the time used in the washing machines, 78% of the time (3.48

hr) people spend waiting for the service. Lifelink is another station where 83% of the time is spent in queues but the station where the people spend the greatest amount of time waiting is in the payment system with 91% of the time in queues.

3.5 Simulation

3.5.1 Simulation model

A simulation model was created to validate the analytical model, to represent different distributions during the day and to evaluate different scenarios in the system that cannot be verify in a steady-state analytical model such as the average waiting time during the day, empty system, queues before opening time and to evaluate the number of consumers the Town Center loses when queues are too long.

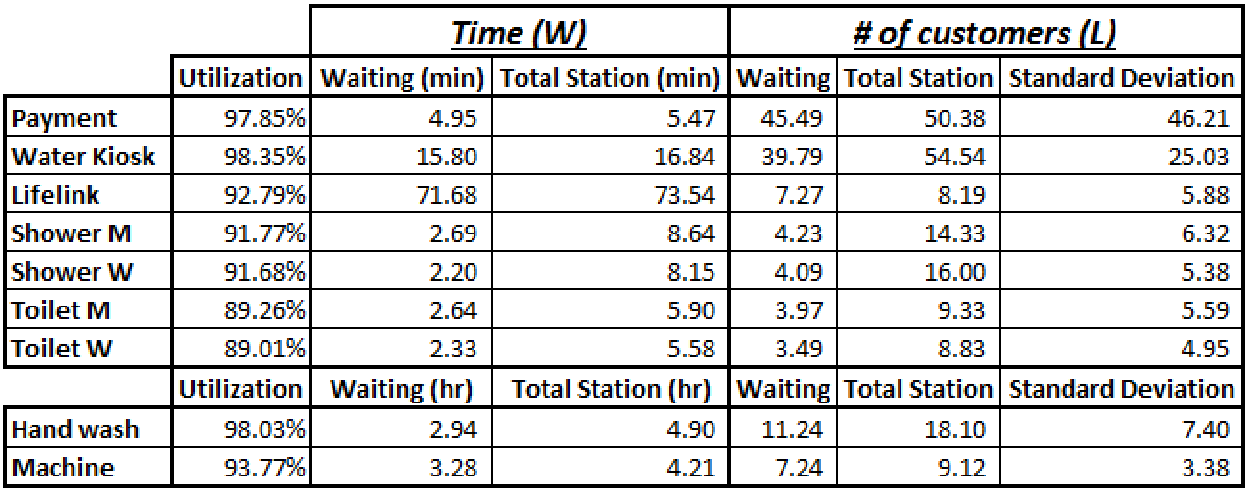
The demand of the center has different distributions depending on the time of the day. This cannot be represented in a standard steady state model since a period of time has to be selected in order to determine the parameters of the model. Although the analytical model was created to cover the peak-hours, a simulation model can helps us understand how the center operates in a dynamic environment where people arrive with different distributions. In the simulation model, the congestion and the waiting times can be revised at different points in time and earlier results have an effect on the following ones. For example, the results and congestion seen in the morning phase have an effect on the results and congestion appreciated in the afternoon.

Another useful characteristic of the simulation model is that the number of people that do not want to wait in long queues can be measured to determine the total losses for the center. When the consumer sees that a lot of people are waiting in queues they could leave the center. Therefore, it is important to consider them in the simulation model.

A simulation model was created using the Arena Simulation Software by Rockwell Automation. Overall, the model represents how people arrive with different distributions depending on the type of service they are willing to take. They go through the payment process and walk to the different service stations. For the water kiosk, the number of jerry cans (20L) every person carries depends on a distribution defined with the consumers' research. Finally, the water consumption is measured to check that the capacity is not exceeded. Furthermore, the simulation model can represent multiple services per person, nevertheless, only single services per person were considered due to lack of complex information. The demand arrivals, service times, and water consumption depends on distributions that were calculated before. The diagram of the simulation model can be seen in Appendix C.

3.5.2 Simulation during peak-hours (steady state)

The main purpose of the simulation model was to validate the analytical model; therefore, the simulation model was run for a long period of time using only the parameters of peak-hours (without different arrival times) to make the comparison with the analytical model. Before analyzing the results, it is important to define the initial parameters such as warm-up period, simulation length, and number of replications to obtain reliable results. A graphical method was used to make a visual inspection of time-series of the output data and determine the warm-up period (Robinson, 2002 & 2007). David Kelton et al. (2004) also suggest that the most practical idea is to make plots of key outputs from within a run, and eyeball when they appear to stabilize. To determine the warm-up period some simulation tests with different replications were made and the graphs for each service station were plotted (Appendix D). Based on the graphical method a warm-up period of 5hours was decided. The number of replications and simulation length were defined based on the work of Robinson (2002 & 2007) where it is stated that the more replications the better and having between five and ten replications as a minimum is important considering a simulation length at least four times longer than the estimated length that is one day. Thus, the model was run during 200 hours with 5 different sets of random data or replications resulting in Table 9. The full results can be seen in Appendix E.



		Time (W)		*# of customers (L)*		
	Utilization	**Waiting (min)**	**Total Station (min)**	**Waiting**	**Total Station**	**Standard Deviation**
Payment	97.85%	4.95	5.47	45.49	50.38	46.21
Water Kiosk	98.35%	15.80	16.84	39.79	54.54	25.03
Lifelink	92.79%	71.68	73.54	7.27	8.19	5.88
Shower M	91.77%	2.69	8.64	4.23	14.33	6.32
Shower W	91.68%	2.20	8.15	4.09	16.00	5.38
Toilet M	89.26%	2.64	5.90	3.97	9.33	5.59
Toilet W	89.01%	2.33	5.58	3.49	8.83	4.95
	Utilization	**Waiting (hr)**	**Total Station (hr)**	**Waiting**	**Total Station**	**Standard Deviation**
Hand wash	98.03%	2.94	4.90	11.24	18.10	7.40
Machine	93.77%	3.28	4.21	7.24	9.12	3.38

Table 9 - Simulation results in a steady state approach

As it can be seen, the results are similar with the analytical model. The utilization is almost the same in all the cases with the same parameters and it can be verified that the stations with the longest queues are Payment system, the Water kiosk and the Hand washing station with 45, 39, and 11 people waiting respectively.

During simulation, the graphs can be plotted to see the behavior of the queue during the day. The Water kiosk, Payment system and Laundry services are important bottlenecks in the system so the queues were plotted to see the peaks that could occur in the Town Center. The payment is a critical service station since all the people need to go through it. For example, in the fourth replication of the simulation, the number of people waiting to do the payment was 271 consumers with an expected waiting time of 27 minutes approximately (Chart 8).

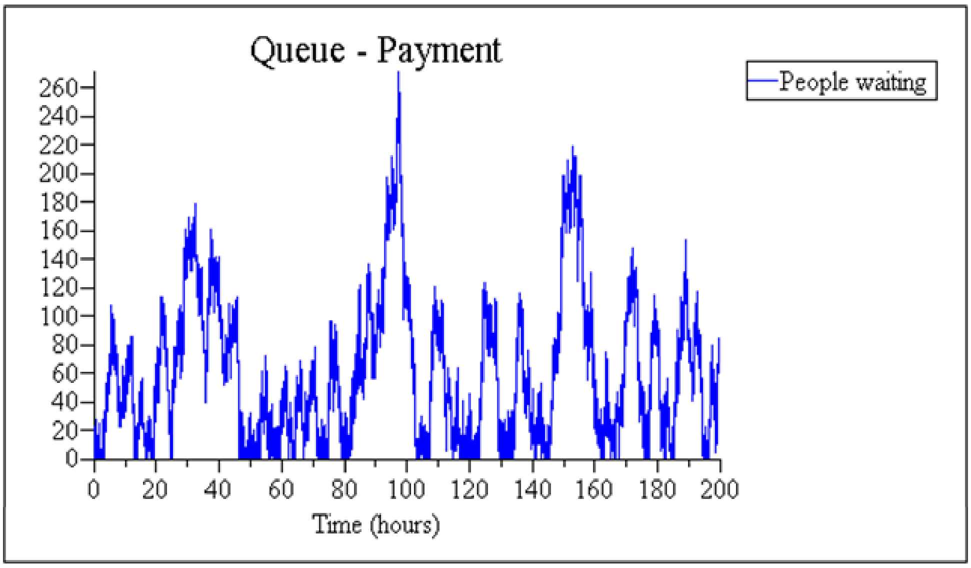


Chart 8 - Queue in Payment station (200 hours)

Regarding the Water Kiosk, it can get really congested some periods of time. For example, during the first run, it can be appreciated that the number of people waiting reached 206 people approximately (Chart 9). The expected waiting time in that situation was 1 hour 16 minutes to be served. This indicates us that in some cases the system could be really congested and queues may be really long.

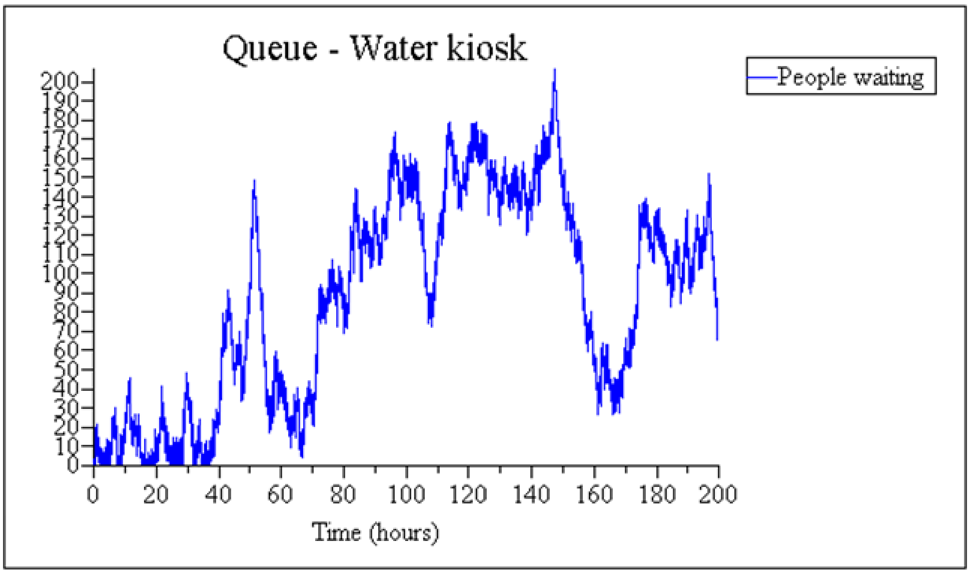


Chart 9 - Queue in Water kiosk (200 hours)

Another critical station is the Laundry services. This is because the station has really long service times and the capacity is restricted meaning that there are not a lot of servers available. In extreme situations, the system can reach long queues with large waiting times. For example, it can be appreciated that the number of people waiting reached 38 and 28 people in the Hand washing service and Washing machines respectively (Chart 10 & Chart 11). The expected waiting time in that situation was 10 hours 8 minutes to be served for the Hand washing and 12 hours 31 minutes for the Washing machines.

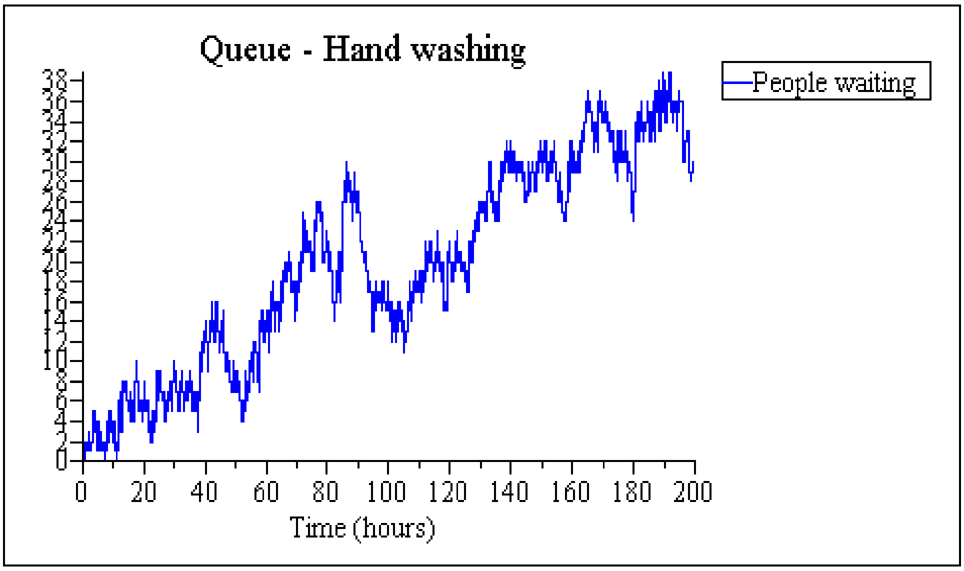


Chart 10 - Queue in Hand washing (200 hours)

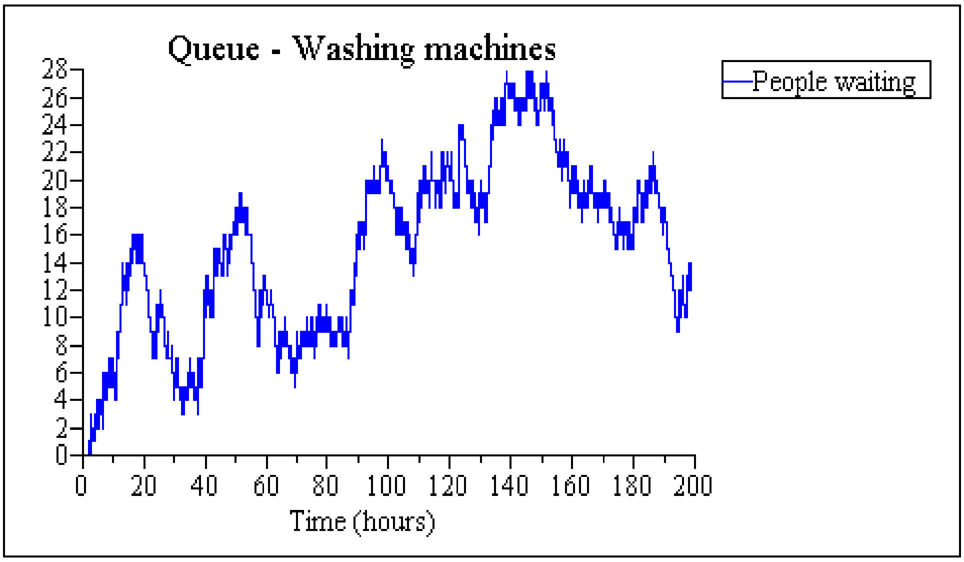


Chart 11 – Queue in Washing machines (200 hours)

It is important to visualize these peaks in the queues since people can decide to leave the Town Center if they see the system is too crowded. Kibera is filled with a lot of water points in every village that do not have the quality the Town Center can deliver but in case the system is really congested people might sacrifice quality for time. Nevertheless, these results considered a steady state approach; therefore, new simulations are presented below considering the opening hours of the water center.

3.5.3 Simulated day at the Town Center

The Town center will have several arrival distributions depending on the time of the day. People use to go to water services more often in the morning to go to work and perform other activities during the day. That is the reason why water points have their peak-hours in the morning. In the afternoon, the demand decreases, being the least congested part of the day. In the evening, people return from work so the services in water points become more congested than in the afternoon.

The simulation was run for the whole day of operations (16 hours) with 50 sets of random data or replications. In this case the simulations were run with an empty system and just for the time the center will be open to simulate the normal operation conditions in the Town Center. The main results are given in Table 10:

		Time (W)		***# of customers (L)***		
	Utilization	**Waiting (min)**	**Total Station (min)**	**Waiting**	**Total Station**	**Standard Deviation**
Payment	73.65%	1.52	1.92	10.52	14.20	18.60
Water Kiosk	73.81%	2.50	3.27	5.00	16.07	8.49
Lifelink	70.45%	23.03	24.44	1.84	2.55	1.99
Shower M	69.03%	1.02	5.50	1.21	8.80	2.86
Shower W	69.19%	0.98	5.47	1.37	10.36	3.21
Toilet M	67.87%	1.25	3.73	1.41	5.48	3.16
Toilet W	67.28%	1.23	3.69	1.38	5.42	3.09
	Utilization	**Waiting (hr)**	**Total Station (hr)**	**Waiting**	**Total Station**	**Standard Deviation**
Hand wash	79.02%	0.49	2.07	1.58	7.11	1.59
Machine	77.86%	0.73	1.51	1.36	2.91	1.11

Table 10 - Simulation results in an operational day

Overall, it can be observed that if different distributions during the day are taken into account, the system appears to be in control and the waiting times are not critical but it is important make a division (morning, afternoon and evening) to analyze the system and to make recommendations for each part of the day because the amount of people is different during the day. People arrive in a great manner during the morning, followed by the evening.

The simulation was done but the results were divided in 3 parts of the day: morning (5:00am-11:00am), afternoon (11:00am-4:00pm) and evening (4:00pm-9:00pm). The average waiting times and average number of people waiting of each part of the day were obtained and are shown in Table 11, each part of the day was simulated with 50 replications:

	Morning				***Afternoon***				***Evening***			
	Utilization	**Waiting Time (min)**	**# of customers (L)**	**Standard Deviation**	**Utilization**	**Waiting Time (min)**	**# of customers (L)**	**Standard Deviation**	**Utilization**	**Waiting Time (min)**	**# of customers (L)**	**Standard Deviation**
Payment	96.60%	2.47	22.64	18.67	48.56%	0.20	0.64	4.73	70.73%	0.14	0.93	2.01
Water Kiosk	94.49%	4.09	10.75	8.60	50.73%	1.09	1.26	4.59	70.43%	0.49	0.94	1.79
Lifelink	89.20%	29.45	3.49	1.85	62.82%	22.24	1.79	1.59	64.70%	12.41	0.96	0.95
Shower M	90.34%	2.30	3.65	3.37	47.11%	0.30	0.20	1.25	65.67%	0.14	0.16	0.60
Shower W	89.88%	2.04	3.81	3.78	47.14%	0.22	0.16	0.95	66.53%	0.15	0.20	0.55
Toilet M	88.49%	2.05	3.09	3.70	46.13%	0.41	0.27	1.11	65.43%	0.33	0.37	0.84
Toilet W	87.82%	2.14	3.21	3.66	45.48%	0.27	0.18	0.61	64.90%	0.28	0.31	0.82
	Utilization	**Waiting Time (hr)**	**# of customers (L)**	**Standard Deviation**	**Utilization**	**Waiting Time (hr)**	**# of customers (L)**	**Standard Deviation**	**Utilization**	**Waiting Time (hr)**	**# of customers (L)**	**Standard Deviation**
Hand wash	78.89%	0.26	1.19	1.58	75.69%	0.53	1.29	1.15	74.19%	0.22	0.73	0.45
Machine	81.93%	0.45	1.27	1.10	73.07%	0.89	1.49	0.60	74.22%	0.59	0.92	0.57

Table 11 – Queuing results divided during the day

The results of simulation are shown in Appendix E with half width of a 95% confidence interval. It can be seen that the morning is when the center has a greater utilization. It was detected that the period of time where the water center will have more congestion is in the morning (5:00am - 11:00am) and the critical stations with the highest congestion are Payment station, Water kiosk and Laundry services.

Payment station

This station is vital since all the people need to pay before using the services. The simulation assuming a service time of 32 seconds for the payment stations was made and the Town Center will need at least 5 people to collect the payments from consumers. Different scenarios for queues were made and two graphs of them are presented below (Chart 12):

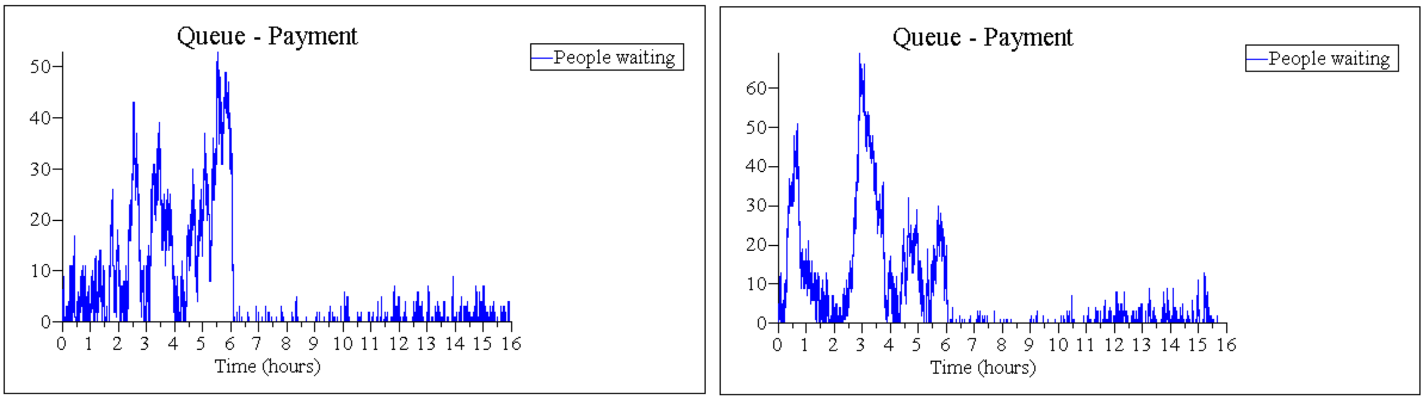


Chart 12 - Payment queues during the day

The critical period of time is during the morning when the system is more congested (first 6 hours) and where most of the queues are formed. On average, 23 people are waiting in line before they are able to pay. This represents around 2.5 minutes waiting considering there are 5 people receiving payments and the process takes 32 seconds. This is not a lot of waiting time but in some situations the queues can grow up to 60 people waiting or more as shown in the previous graph. There are also critical moments where 180 people are waiting in line as shown in Appendix F – Maximum peak values.

Water Kiosk

To serve the estimated number of people and fulfill the demand, the water center needs to make use of the 15 taps installed. If HNP does not use 15 taps in the morning the system can create a large amount of queues. It is assumed approximately 1 minute on average to fill a 20liter JerryCan. Some simulations were made and some scenarios are presented below (Chart 13):

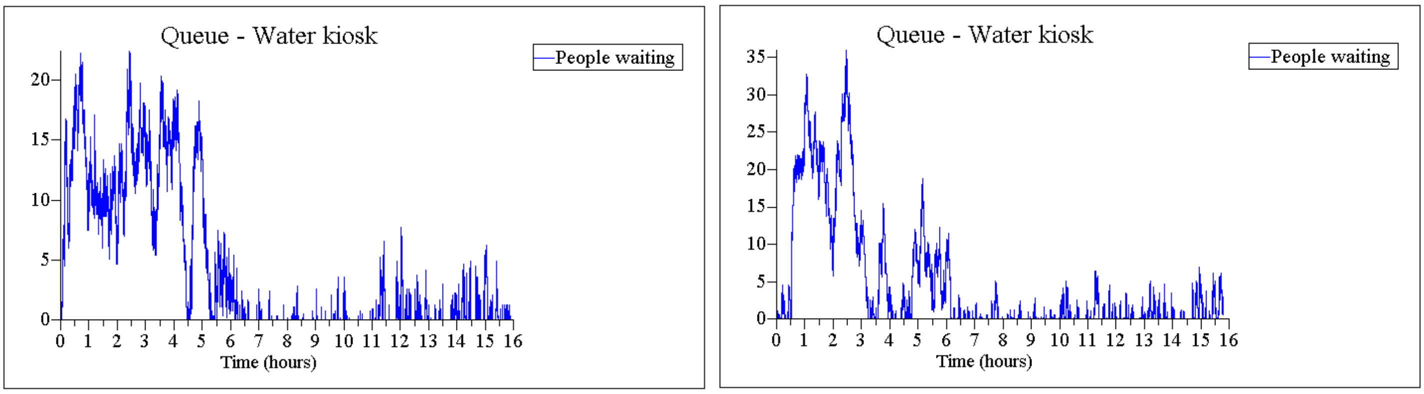


Chart 13 - Water Kiosk queues during the day

The critical period of time is during the morning when the system is more congested and where most of the queues are formed. On average, 11 people are waiting in line before they are able to fill their jerry cans with water. This represents 4 minutes waiting on average. Each person fills on average 5.32 jerry cans per visit. In some situations 73 people can be waiting in line as shown in Appendix F – Maximum peak values.

Laundry Services

The laundry services are also critical services because of their long service times: 1 hour on average for washing machines and 2 hours for hand washing. Also, the number of servers is limited so HNP does not have a lot of flexibility in the system. Different scenarios for queues were made and one of them is presented below (Chart 14):

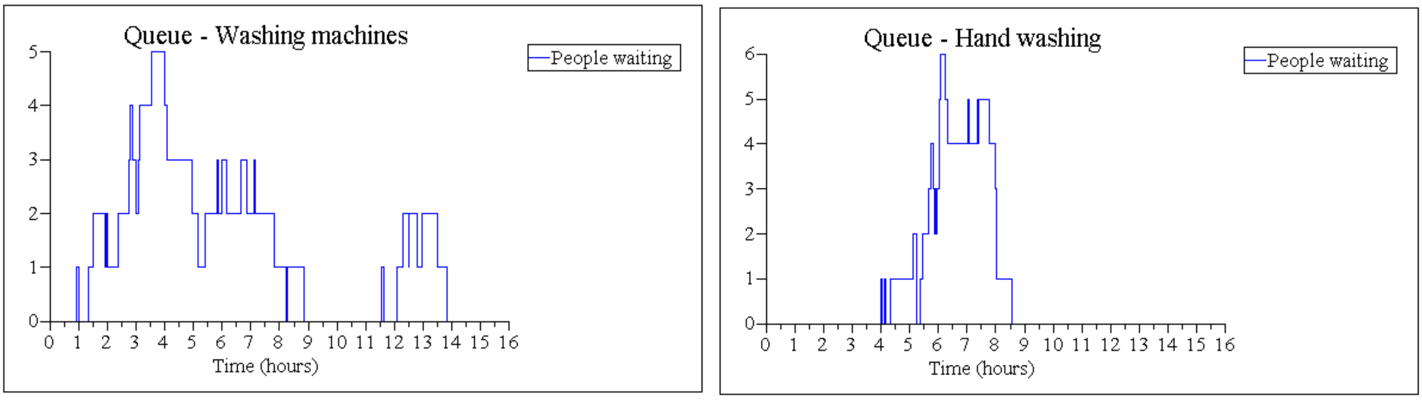


Chart 14 - Laundry queues during the day

The critical period of time is during mornings and afternoons when the system is more congested and were most of the queues are formed. On average, 2 people are waiting in line in each service before they are able to do their laundry. This represents around 30-50 minutes waiting. There are also critical moments where 10 -11 people need to wait for 2 up to 3 hours in line as shown in Appendix F – Maximum peak values.

3.6 Comparison between analytical model & simulation

Both, the analytical model and simulation model, need to show the same results, however, some differences can be observed depending on the parameters each model has. Sometimes randomness is a factor in the differences between each model but other times it depends in other factors such as simulation length, replications, and different arrivals during the simulation, between other factors. A comparison is made taking into account the simulation model during the day (16 hours) versus the analytical model with three different scenarios when the center opens in the morning (5:00am): empty system, full servers, and average number of people waiting.

3.6.1 Empty system

In the previous results (Table 11), the simulation model during the day assumes that all the stations are empty at the beginning of the day. That means that the system is empty every day at 5:00am in the morning and the demand arrives depending on the distribution. If the results of the analytical model (Table 7) are considered and a comparison is made with the simulation model (Table 11), it can be seen that the utilization decreased in the simulation model in all the service stations. Also, the waiting times and the number of customers waiting are reduced. This is because the Town Center started with an empty system; therefore, it takes time to fill up the stations and for congestion to take place. Moreover, the simulation length is just 6 hours in the morning (5:00am – 11:00am) so it does not allow the queues to grow as it might occur with long simulation lengths or in the analytical model that has a steady-state approach.

3.6.2 Full servers

Considering the previous scenario people could notice that the center is empty at 5:00am when the Town Center is opening. Thus, they might create queues even before the center open its doors and start operating. A new simulation assuming that all the servers are busy at the beginning was made.

This exemplifies that people are waiting in line before the center opens to be the first using each service and when the center opens all the stations are filled up. The results are shown in Table 12:

	Morning				Afternoon				Evening			
	Utilization	Waiting Time (min)	# of customers (L)	Standard Deviation	Utilization	Waiting Time (min)	# of customers (L)	Standard Deviation	Utilization	Waiting Time (min)	# of customers (L)	Standard Deviation
Payment	96.11%	2.38	21.52	15.71	48.26%	0.16	0.53	2.01	70.49%	0.15	0.97	2.04
Water Kiosk	96.00%	5.03	13.38	8.13	50.27%	1.13	1.24	3.75	70.06%	0.48	0.91	1.67
Lifelink	88.19%	26.52	2.96	1.78	59.98%	25.55	1.50	1.29	70.99%	14.14	1.21	1.02
Shower M	89.48%	1.81	2.83	3.46	46.77%	0.21	0.14	0.72	66.57%	0.16	0.19	0.53
Shower W	90.40%	1.64	3.07	3.26	46.13%	0.14	0.11	0.83	65.70%	0.11	0.16	0.59
Toilet M	88.27%	1.83	2.76	3.39	45.47%	0.23	0.15	0.66	64.44%	0.28	0.30	0.87
Toilet W	88.66%	2.04	3.08	3.53	45.90%	0.30	0.19	1.04	64.52%	0.26	0.28	0.79
	Utilization	Waiting Time (hr)	# of customers (L)	Standard Deviation	Utilization	Waiting Time (hr)	# of customers (L)	Standard Deviation	Utilization	Waiting Time (hr)	# of customers (L)	Standard Deviation
Hand wash	92.34%	0.55	2.38	1.37	64.69%	0.32	0.65	0.38	66.93%	0.09	0.30	0.46
Machine	88.67%	0.66	1.56	1.12	66.43%	0.62	0.86	0.52	64.79%	0.34	0.60	0.36

Table 12 – Results with full servers at 5:00am

As it can be observed, the utilization increases in critical stations such as Water Kiosk and Laundry services considering the previous results in Table 11. The laundry services are clearly noticeable because all the servers are being used since the beginning so that results in a higher congestion. The laundry stations do not need to wait for the center to fill up, nevertheless, the results show still a lower utilization than the analytical model (Table 7). Although the system fills-up the stations faster from the beginning, the simulation length (5:00am – 11:00am) does not allow the queues to grow as it might occur with long simulation lengths or in the analytical model that has a steady-state approach.

3.6.3 Average number of people waiting

In this scenario, there are long queues of people waiting before the center opens its doors that fill up all the stations immediately. However, the amount of people that have arrived is more than the number of serves as in the previous scenario so the people have to wait in line (average number of people waiting in steady-state) until one server is available.

	Morning				Afternoon				Evening			
	Utilization	Waiting Time (min)	# of customers (L)	Standard deviation	Utilization	Waiting Time (min)	# of customers (L)	Standard deviation	Utilization	Waiting Time (min)	# of customers (L)	Standard deviation
Payment	96.17%	2.40	22.10	13.44	48.03%	0.09	0.30	1.94	70.62%	0.14	0.92	2.11
Water Kiosk	96.26%	4.56	12.15	7.87	49.61%	1.08	1.16	3.18	70.98%	0.49	0.95	1.86
Lifelink	87.51%	25.54	2.76	1.64	52.22%	17.88	0.91	1.00	65.21%	13.31	1.06	0.96
Shower M	90.22%	1.80	2.83	3.55	46.95%	0.22	0.15	0.54	66.04%	0.17	0.20	0.56
Shower W	89.93%	1.52	2.81	4.00	46.02%	0.07	0.05	0.52	66.54%	0.12	0.16	0.61
Toilet M	88.73%	2.02	3.04	3.27	45.51%	0.39	0.23	0.63	63.73%	0.25	0.27	0.85
Toilet W	89.71%	2.24	3.40	3.30	45.25%	0.22	0.14	0.73	63.83%	0.28	0.31	0.78
	Utilization	Waiting Time (hr)	# of customers (L)	Standard deviation	Utilization	Waiting Time (hr)	# of customers (L)	Standard deviation	Utilization	Waiting Time (hr)	# of customers (L)	Standard deviation
Hand wash	98.52%	1.84	7.22	4.20	61.21%	0.14	0.33	0.17	69.96%	0.11	0.36	0.34
Machine	98.36%	2.14	4.78	2.43	62.20%	0.67	0.74	0.25	70.78%	0.34	0.64	0.38

Table 13 – Results with average number of people waiting at 5:00am

It is shown that the utilization increased in some stations versus other scenarios (Table 11 & Table 12). Moreover, it can be seen that the utilization of the Laundry services is higher than the utilization in the analytical model (Table 7) and the number of people waiting increased if they are compared with previous results (Table 11 & Table 12). Nevertheless, the number of people waiting specifically in the Laundry services (Hand wash & Washing machines) is still less than the analytical model (Table 7).

In the previous scenarios, the analytical model tried to be replicated but the simulation length is a factor to consider in the results. When the simulation runs for the period of time that the center is operating (morning: 5:00am-11:00am, afternoon: 11:00am – 4:00pm, evening: 4:00pm – 9:00pm), the number of hours is too short for queues to grow as it occurs with long simulation lengths or with the steady-state analytical model.

Some graphs of the simulation during peak-hours (steady state) were taken into account to show how simulation length is an important factor to consider on how much queues can grow. The graphs of the Laundry services simulated for 200 hours (Chart 15) are shown below:

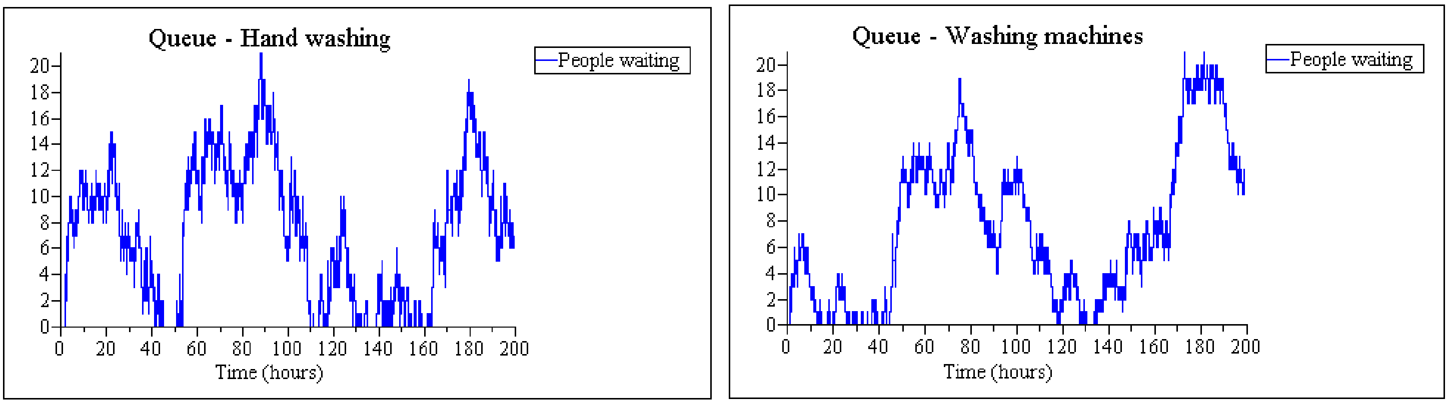


Chart 15 – Laundry services in a steady state simulation

In the graphs it can be appreciated how the largest queues in the laundry services occur in periods of congestion of more than 30 hours. Therefore, the same behavior and results cannot be expected in short simulations as the ones in the Town Center because the system does not have time for queues to grow as in a steady state approach.

As it can be observed there are three scenarios on how the Town center can start operations: empty system, full servers, or with average number of people waiting (number based on the steady state approach). HNP made a research on 105 water centers in which the owners were interviewed to know more about the characteristics of the water points in Kibera, including aspects such as opening hours, how they obtain the water, relation with water vendors, price, and shortages between other topics. In this research, it was found that the majority of the water points (51%) open at 6:00am because they believe that most of the people come to the water points between 6:00am and 10:00am. Moreover, 25% of the water owners open their centers at 7:00am, and only 14% of all the respondents open at 5:00am in the morning. With this information, it is assumed that the Town Center starts with an empty system. Thus, in the following simulations the water system will start with an empty system and people will arrive from 5:00am onwards to the Town Center.

4 Sensitivity analysis

4.1 Simulation during the weekend

Based on some research made by HumanNeeds Project concerning water points in Kibera the demand increases during the weekends. The increase on demand in Town Center can present congestion problems during the day, especially in the morning because the center cannot handle more capacity. It is assumed that demand increases on average 30% which causes congestion in the system most of the time. A simulation was made and the results are shown in Table 14:

	Morning				***Afternoon***				***Evening***			
	Utilization	**Waiting Time (min)**	**# of customers (L)**	**Standard Deviation**	**Utilization**	**Waiting Time (min)**	**# of customers (L)**	**Standard Deviation**	**Utilization**	**Waiting Time (min)**	**# of customers (L)**	**Standard Deviation**
Payment	99.64%	10.48	124.70	73.84	58.24%	4.34	19.85	56.74	76.21%	0.16	1.38	2.77
Water Kiosk	99.41%	31.64	102.29	58.31	94.30%	53.02	114.41	76.03	91.42%	3.22	8.05	6.36
Lifelink	96.04%	46.23	6.46	3.94	83.57%	75.02	6.26	2.54	83.50%	40.28	4.19	1.69
Shower M	98.60%	20.39	39.25	24.24	82.09%	27.04	32.55	35.50	84.86%	1.03	1.53	2.36
Shower W	98.59%	22.37	51.26	28.28	83.39%	30.23	43.67	44.06	85.69%	1.01	1.80	2.39
Toilet M	98.53%	18.06	33.62	18.26	78.63%	23.39	26.54	27.44	84.15%	1.35	1.93	2.36
Toilet W	98.59%	19.69	36.23	21.08	78.89%	23.63	26.85	31.68	85.01%	1.60	2.30	2.52
	Utilization	**Waiting Time (hr)**	**# of customers (L)**	**Standard Deviation**	**Utilization**	**Waiting Time (hr)**	**# of customers (L)**	**Standard Deviation**	**Utilization**	**Waiting Time (hr)**	**# of customers (L)**	**Standard Deviation**
Hand wash	87.84%	0.59	3.44	2.32	96.29%	1.87	6.86	1.48	95.21%	1.63	5.71	1.15
Machine	90.80%	0.73	2.24	1.69	88.68%	1.80	4.05	1.12	89.89%	1.92	3.70	1.14

Table 14 - Simulation during the weekend

The results showed high congestion in the system especially in the morning. The servers in the payment system were increased to 6 people receiving payments but they are still not sufficient. In this scenario, more servers are needed if it is intended to fulfill all the demand. However, some measurements should be taken during weekends to try to measure in what percentage does the demand increases but based on the calculations it is probable that the capacity might be exceeded.

4.2 Number of servers

Sometimes a good solution can be to increase the number of servers to be able to fulfill the demand. If the number of servers is increased, the Town Center will have more capacity and it will be able to serve more people. The number of servers is also related with the service time that is how much time it is needed to serve the people. If the service times decrease it might be needed fewer servers but if the service times increase the Town Center will need more servers to fulfill the demand.

For example, in the payment station it is critical to measure the real service time once the Town center starts operating because if it increases a lot, the capacity will be exceeded. For example, if the payment process takes 1 minute, HNP will need at least 9 people receiving payment if not the system will exceed the capacity creating really long queues. The process was simulated with 8 people receiving the payments and long queues of approximately 350 people are created as shown in the following graph (Chart 16).

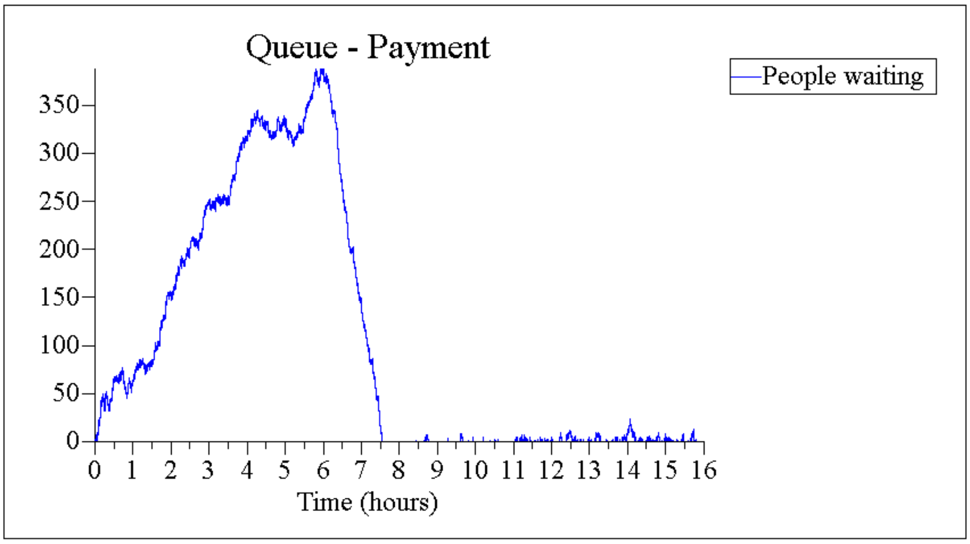


Chart 16 - Payment queue in case the capacity is exceeded

Therefore, it is important to notice that if there are not sufficient servers or people accepting payments big queues can be formed.

Based on the initial configuration where 50% of the people arrive in the morning (5:00am-11:00am), 20% in the afternoon (11:00am-4:00pm) and 30% in the evening (4:00pm-9:00pm) HNP can also have different number of people serving during the day. For example: there can be 5 people collecting payments in the morning, 3 in the afternoon and 4 in the evening to organize in a better way the resources. The results are shown in the following graph (Chart 17):

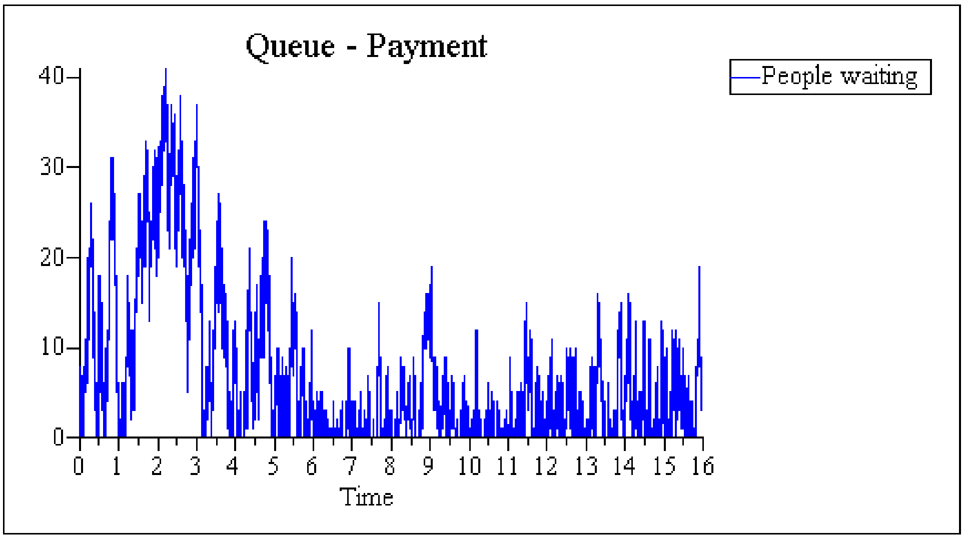


Chart 17 - Payment queues by reducing servers

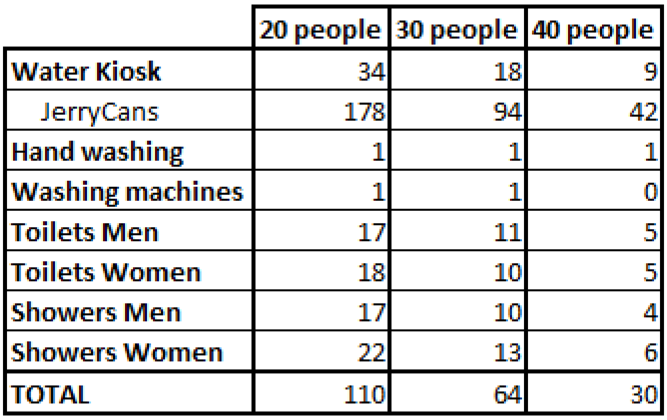
HNP can decrease the number of people receiving payments only when there are not risks of congestion that is mainly in the afternoon and in the evening but it must be taken into account the service times and the congestion in the system before allocating in a different way the resources.

4.3 Long queues, people leaving the center

4.3.1 Payment station with 5 servers

As it can be seen in Appendix F – Maximum peak values, sometimes queues can grow a lot. If queues grow too fast, people might decide to leave the center. Some simulations were made assuming people leave when the queues are large (20 - 40people) in the payment station to measure how many consumers HNP will lose and how much money it represents in a normal weekday. The decision to consider the payment station is because after people make their payment they will stay in the system. It is assumed that they have already made an investment so probably they will not leave the system until they receive their services. In this scenario, it is assumed that people go to other water centers in the area because the queues are too long in the Town Center.

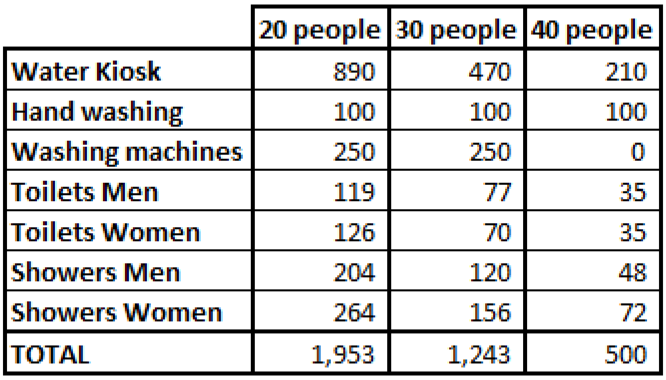
The results are the following with different queue limit (Table 15):



	20 people	30 people	40 people
Water Kiosk	34	18	9
JerryCans	178	94	42
Hand washing	1	1	1
Washing machines	1	1	0
Toilets Men	17	11	5
Toilets Women	18	10	5
Showers Men	17	10	4
Showers Women	22	13	6
TOTAL	110	64	30

Table 15 - Consumers lost per day due to long queues (5 servers)

The results showed that on average HNP might lose 110 consumers per day if they decide to leave the center (the payment queue is with 20 people or more). Other scenarios show that with a queue limit of 30 and 40 people HNP loses on average 64 and 30 consumers per day. These consumers that decide to leave represent lost sales for the Town Center and if they are quantified in Kenyan Shillings (KSH) the money lost will be (Table 16):



	20 people	30 people	40 people
Water Kiosk	890	470	210
Hand washing	100	100	100
Washing machines	250	250	0
Toilets Men	119	77	35
Toilets Women	126	70	35
Showers Men	204	120	48
Showers Women	264	156	72
TOTAL	1,953	1,243	500

Table 16 - Money lost per day due to long queues (5 servers)

If HNP lose 110 consumers per day the amount lost will be 1,953 KSH (16.59 EUR approximately). Although it only represents 2% per day, it represents the salary of 2 staff employees per day. This scenario assumed that HNP has at least 5 people receiving payments in the initial station. If it is not the case, HNP might lose more consumers per day as shown in the following scenario.

4.3.1 Payment station with 4 servers

The payment station is an important station within the water system since it is the first filter in the process. If people see that long queues are present at the beginning, they might decide to go to other water points. In this scenario, it is assumed that HNP only has 4 servers in the payment station. The results are the following with different queue limit (Table 17):

	20 people	30 people	40 people	50 people
Water Kiosk	178	170	163	156
JerryCans	954	904	864	835
Hand washing	5	5	4	4
Washing machines	3	3	2	2
Toilets Men	100	97	92	89
Toilets Women	102	100	94	93
Showers Men	103	103	96	94
Showers Women	129	122	113	108
TOTAL	620	600	564	546

Table 17 - Consumers lost per day due to long queues (4 servers)

The results showed that on average HNP might lose 620 consumers per day if they decide to leave the center when the payment queue is with 20 people or more. Other scenarios show that with a queue limit of 30 and 40 people HNP loses on average 600 and 564 consumers per day respectively. These consumers that decide to leave represent lost sales for the Town Center and if they are quantified in Kenyan Shillings (KSH) the money lost will be (Table 18):

	20 people	30 people	40 people	50 people
Water Kiosk	4,770	4,520	4,320	4,175
Hand washing	500	500	400	400
Washing machines	750	750	500	500
Toilets Men	700	679	644	623
Toilets Women	714	700	658	651
Showers Men	1,236	1,236	1,152	1,128
Showers Women	1,548	1,464	1,356	1,296
TOTAL	10,218	9,849	9,030	8,773

Table 18 – Money lost per day due to long queues (4 servers)

If HNP lose 620 consumers per day the amount lost will be 10,218 KSH (86.83 EUR approximately). This money lost represents 11% of the expected revenue per day. It also represents the salary of 10 staff employees per day. As it can be observed the number of consumers can make a difference in how queues increase. If queues are too long people will leave the center and the revenue will be reduced.

5 Improvements & feasibility

5.1 Increasing the number of servers

The number of servers is a constraint that can be changed in order to adjust the capacity in the water system. One of the solutions for the critical stations or bottlenecks is to increase the number of servers and therefore the capacity to serve more people. Nevertheless, this is sometimes not feasible due to system constraints or financial limitations. Overall, the Town Center has some space limitation. There is not space for future expansion; most of the stations were already defined so it is difficult to increase the number of servers.

For the payment services, it is needed more people to receive the payments but the organization does not want to hire more people (they already hired 30 staff members to operate the center) and it is expensive to pay them every month. Nevertheless, the management needs to focus on the stations with the greatest flow of people so they can increase the capacity by allocating more of the current resources. For the Water Kiosk, there is no room to install more taps. However, installing double hoses per tap is a feasible solution to increase the number of servers. Toilets, showers and hand washing stations cannot expand since the facilities are already in place with no more space to expand. Finally, for the washing machines more servers can be installed but the space available in the Laundry services is a restriction and it needs to be considered before buying new machines.

5.2 Top-up cards

The payment station is one of the critical stations due to the flow of people it has especially during mornings. The top-up card is a personal card where people can charge an amount of money in it to use it for all the services in the Town Center. Thus, top-up cards are a solution for the payment station since the people that have money in their cards will go directly to the service stations avoiding and reducing the queues in the payment station.

Kibera is a poor settlement; therefore, people will struggle to put big quantities on money in the top-up cards. Based on this problematic, a simulation was performed assuming that only 25% of the people have money in their cards when they arrive to the Town Center. This small percentage of people will reduce the number of people going through the payment service and it will decrease queues in the payment station as it can be shown in Table 19:

	Without top-up cards			***25% population Top-upcards***		
	Utilization	**Waiting Time (min)**	**# of customers (L)**	**Utilization**	**Waiting Time (min)**	**# of customers (L)**
Payment	96.60%	2.47	23	90.48%	1.58	7
Water Kiosk	94.49%	4.09	11	95.27%	4.32	11
Lifelink	89.20%	29.45	3	87.14%	24.43	3
Shower M	90.34%	2.30	4	89.37%	1.66	3
Shower W	89.88%	2.04	4	90.75%	2.17	4
Toilet M	88.49%	2.05	3	88.60%	2.21	3
Toilet W	87.82%	2.14	3	89.79%	2.79	4
	Utilization	**Waiting Time (hr)**	**# of customers (L)**	**Utilization**	**Waiting Time (hr)**	**# of customers (L)**
Hand wash	78.89%	0.26	1	79.40%	0.28	1
Machine	81.93%	0.45	1	82.38%	0.48	1

Table 19 - Comparison between cash payments vs. 25% of top-up cards

As it can be seen in the previous table, the queues are reduced from 23 people to 7 people waiting. Thus, top-up cards is a good solution to decrease the number of people waiting in the payment station. Nevertheless, the success of them depends on the implementation and an efficient procedure of topping-up the cards.

HumanNeeds Project desires a top-up system because that will help them create databases of consumers and also it will help the implement of a loyalty program. The organization has been in contact with BebaPay, a company providing that type of service in Kenya, to implement the system in the Town Center. BebaPay works with the Equity Bank that is in charge of topping-up the cards.

The top-up cards system will become a reality in the Town Center but it is still not defined when since some modifications in the center have to take place before launching the system. The center needs to change its structure to be able to assure a safe environment for the Equity Bank. This means that a small bunker has to be created to hold in a safe way the money that bank will receive.

The top-up cards system is feasible since it is already planned by the organization and it is going to be helpful to reduce the number of people going through the payment process while capturing useful information to create a database of consumers. In order to reduce the queues the procedure to top-up the cards should be as fast and efficient as possible. Otherwise, queues can be present in the Equity Bank as well if the capacity is exceeded. An advantage of the Equity Bank is that the top-up cards can be charged in other Equity Bank facilities so that could help prevent congestion in the Town Center.

5.3 Balancing the flow of people

The best solution when there are queuing problems is to balance the flow of people during the day. This can be done through different prices during the day, with discounts in the services or with promotions only if the capacity is not fulfilled in other periods during the day. Assuming HNP can decrease 10% of the demand in the morning shift, the distribution will be 40% of people going in the morning (5:00am – 11:00am), 25% of people going in the afternoon (11:00am – 4:00pm), and 35% of people going in the evening (4:00pm – 9:00pm). With this flow of people during the day, the behavior of the Town Center will be the following:

Payment:

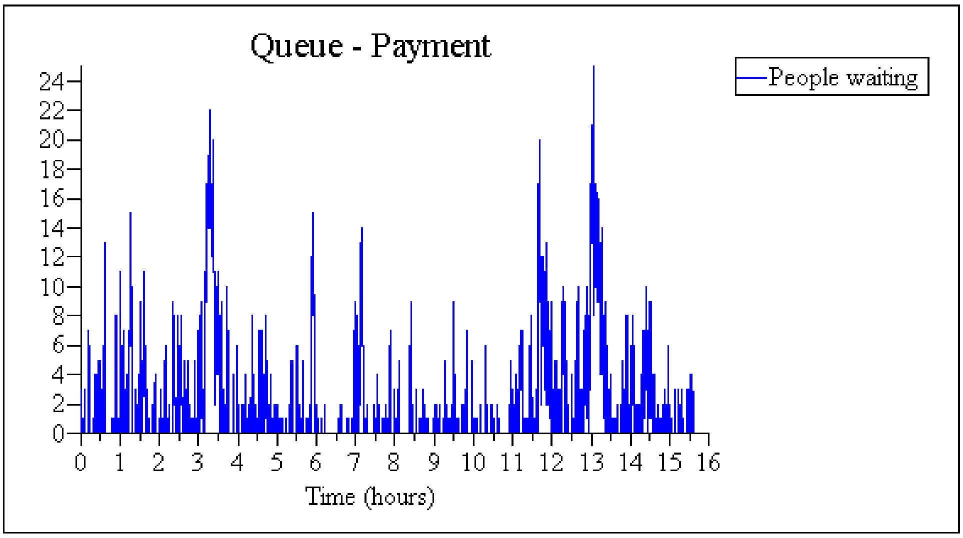


Chart 18 - Payment queues during a balanced day

Water Kiosk:

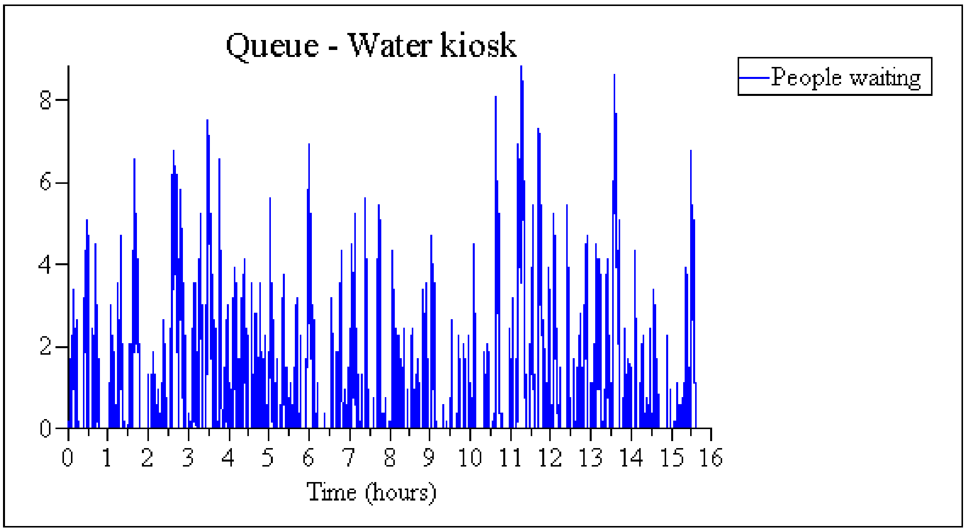


Chart 19 - Water Kiosk queues during a balanced day

Laundry services:

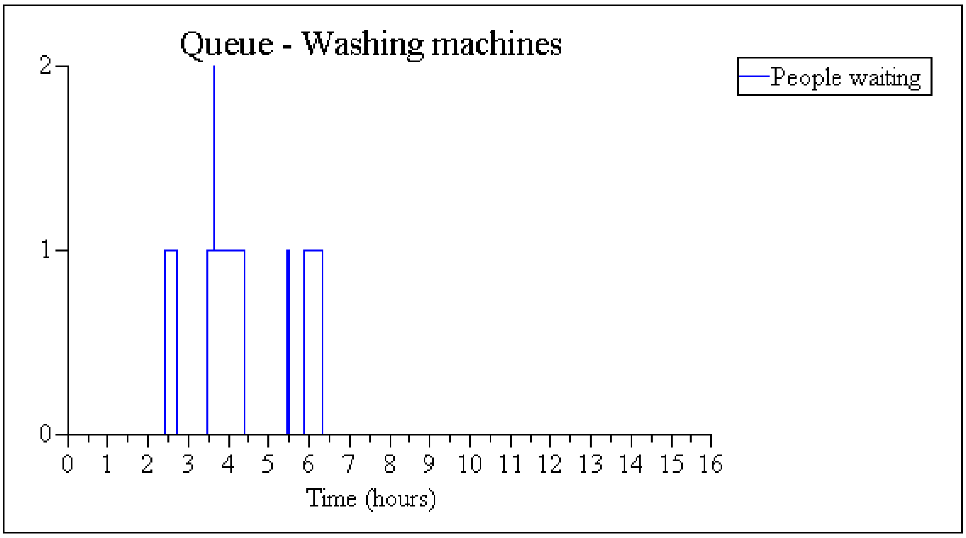


Chart 20 - Washing machines queues during a balanced day

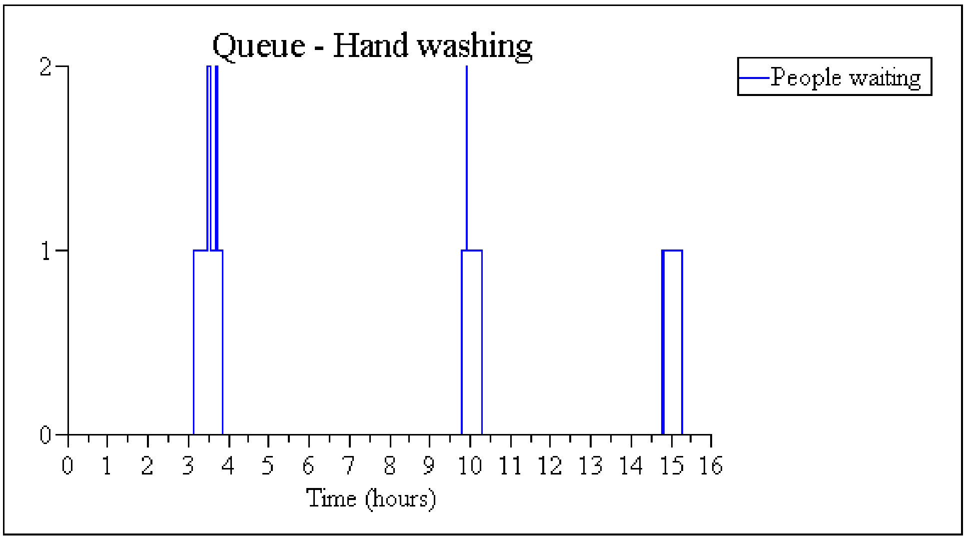
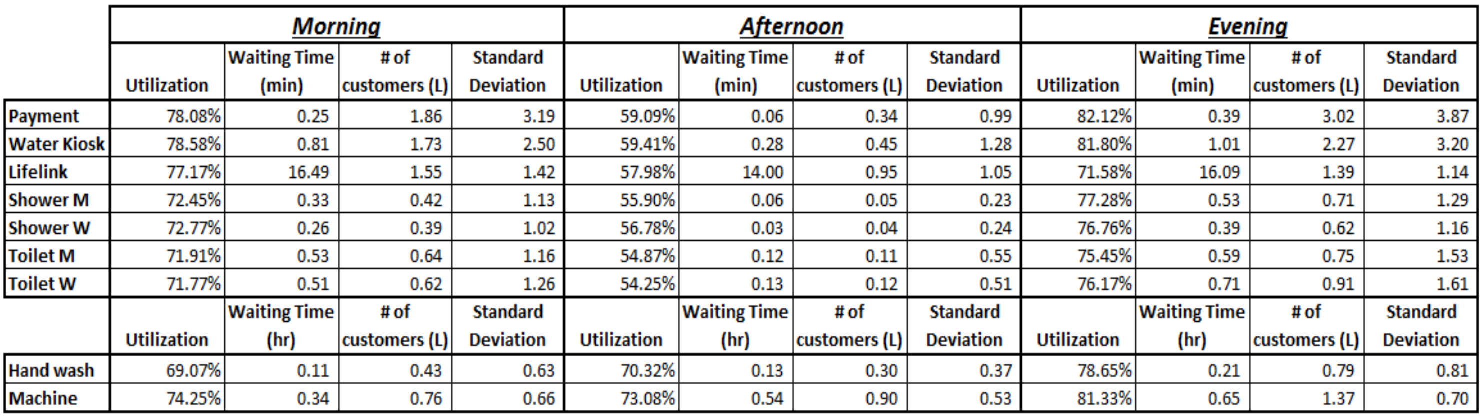


Chart 21 - Hand washing queues during a balanced day

As it can be appreciated in the graphs, the demand is balanced and the queues are more or less the same during the day. The peaks and the queue lengths are reduced so the Town Center operates in a better way.



	Morning				Afternoon				Evening			
	Utilization	Waiting Time (min)	# of customers (L)	Standard Deviation	Utilization	Waiting Time (min)	# of customers (L)	Standard Deviation	Utilization	Waiting Time (min)	# of customers (L)	Standard Deviation
Payment	78.08%	0.25	1.86	3.19	59.09%	0.06	0.34	0.99	82.12%	0.39	3.02	3.87
Water Kiosk	78.58%	0.81	1.73	2.50	59.41%	0.28	0.45	1.28	81.80%	1.01	2.27	3.20
Lifelink	77.17%	16.49	1.55	1.42	57.98%	14.00	0.95	1.05	71.58%	16.09	1.39	1.14
Shower M	72.45%	0.33	0.42	1.13	55.90%	0.06	0.05	0.23	77.28%	0.53	0.71	1.29
Shower W	72.77%	0.26	0.39	1.02	56.78%	0.03	0.04	0.24	76.76%	0.39	0.62	1.16
Toilet M	71.91%	0.53	0.64	1.16	54.87%	0.12	0.11	0.55	75.45%	0.59	0.75	1.53
Toilet W	71.77%	0.51	0.62	1.26	54.25%	0.13	0.12	0.51	76.17%	0.71	0.91	1.61
	Utilization	Waiting Time (hr)	# of customers (L)	Standard Deviation	Utilization	Waiting Time (hr)	# of customers (L)	Standard Deviation	Utilization	Waiting Time (hr)	# of customers (L)	Standard Deviation
Hand wash	69.07%	0.11	0.43	0.63	70.32%	0.13	0.30	0.37	78.65%	0.21	0.79	0.81
Machine	74.25%	0.34	0.76	0.66	73.08%	0.54	0.90	0.53	81.33%	0.65	1.37	0.70

Table 20 - Results of a balanced water center during the day

It can be seen (Table 20) that if HNP achieves a balance during the day, HNP can decrease the queues in the morning. Balancing the flow of people is vital to smooth the operations in the Town Center and reduce the congestion in the system. There are several strategies that can be implemented in the center to balance the flow of people: price differentiation and promotions. Balancing the flow of people is vital to help us reduce queues and it prevents that people leave because queues are too long.

5.3.1 Price differentiation

Price differentiation usually is a good option to balance the flow of people because even some slightly changes in price can influence people to attend the center in a different time and prevent queues. Nevertheless, the situation in Kibera is more complex. The price is Kibera is fixed by the water cartel. This group of people is the one that decides the price of each JerryCan. The water points should respect those prices if not some threats and retaliations can occur. Therefore, in this case the Town Center will not take the price differentiation approach at the beginning. HumanNeeds Project has been in constant communication with the water cartel to have a smooth introduction in the area and this strategy can alter the situation.

5.3.2 Promotions

Although price differentiation cannot be done, a strategy involving promotions with the top-up cards will allow the management to balance the flow of people during the day. The Town Center needs to keep the price fixed during the day but promotions or strategies regarding extra points in the top-up cards will help to balance the flow in the services stations.

Extra points can be given in the top-up cards to the people that go in the afternoon/evening. For example: if people decide to buy services in the morning they can pay 20 KSH for 4 jerry cans, nevertheless, a strategy can take place that if people go in the afternoon they will receive 10% of extra points (1 point = 1 KSH) in their cards so they will be able to collect 2 KSH if they buy those 4 jerry cans in the afternoon. People will be able to accumulate points and get free services with them. In this way, the agreement with the water cartel will not be in risk and the management of the Town Center will balance the flow of people during the day reducing queues and preventing people on leaving the center.

5.4 Performance measurements

Every system needs performance measurements to maintain operations under control and detect anomalies when they happen. Furthermore, performance measurements are indicators that can specify what can be wrong in the system and what is the actual performance at a given time in order to compare them to previous results. The Town Center needs to have performance measurements to be able to understand the water system and control future operations.

First, it is important to measure if the capacity is the same in the system. It is important to note that the capacity specified was based on service time's estimations so the capacity needs to be compared with the actual service times of every station. The number of people per hour needs to be an indicator in the water system because it is necessary to indicate the utilization of the water center. Utilization is a performance measurement that provides vital information. If utilization goes over 100% it indicates that the capacity of the system is exceeded. Therefore, capacity needs to be increased or the number of people entering the system needs to be limited. If the capacity in the Town Center is exceeded and HNP cannot invest in new servers, a limitation needs to take place in the payment station. Utilization also provides information on how the distribution of people is during the day, thus, it is a good indicator to determine if the system has sufficient capacity to balance the flow of people.

6 Conclusions

In this master thesis project two different models were built to understand the operations in a water center in Kibera, Kenya. Working in one of the biggest slums in Africa was a real challenge since information and data available is scarce and difficult to obtain. People in developing settlements have a lot of different small scale providers to obtain water from and water shortages can occur often affecting the forecast and the information available in each water point. In this project, several methodologies involving consumers' research, surveys and data from several water points in Kibera helped to obtain estimations about the demand, arrival times, and service times. Furthermore, there is a lack of models in the literature that evaluate water systems and that analyze their operations in developing countries. Nevertheless, the models presented (analytical model and simulation model) are efficient tools that facilitate the analysis and that let us visualize possible risks in the operations of water systems.

The results from the analysis were validated between the analytical model and the simulation model. In them, it can be shown that 3 critical stations are present in the Town Center: Payment station, Water Kiosk, and Laundry services. Although both models show some differences due to randomness in the sets of data, the simulation model tend to have a steady state approach as the analytical model if the correct warm-up period is defined and if long simulation lengths and multiple replications are considered.

Moreover, simulations were made only considering the opening hours (16 hours) with different distributions (morning, afternoon, and evening), showing that the center was under control with short queues and no specific congestion problems. However, it was important to check the simulation model in different stages of the day to appreciate how is the congestion during the day. The results showed that the water center has three critical stations: payment station, water kiosk and laundry services and that the morning (5:00am – 11:00am) is the period of time where the water center has more congestion. In these simulations it is important to notice that even when the same parameters were introduced, less congestion can be observed against the analytical model because it started with an empty system so at the beginning the center needs some time for the stations to become congested. Moreover, the duration is limited to only 6 hours so queues cannot grow a lot as in the steady state approach.

It was also observed that when the center starts with all the servers being used, the utilization increases in some stations such as the laundry services and water kiosk. This is because the period of time for the system to fill-up is eliminated. However, the queue length was under the average number of people waiting in the steady state models. Furthermore, the system was initialized with full servers and the average number of people waiting (based on the steady state model). This scenario showed that the utilization increased but the queues were still under the average queue length stated in the analytical model. With these simulations it can be appreciated that the utilization can be increased by filling up the system at the beginning but the average queue length is still dependent on the simulation length. The behavior of a steady state model with longer queues was not replicated in day simulations (16 hours) since simulation length was short for queues to grow in a great manner.

Some risks were appreciated in the system especially during weekends when the demand increases which can cause people to leave the center if there are a lot of people waiting in lines. Therefore, it is important to increase the number of servers or allocate them correctly to adjust the capacity in the system and to provide a good service in each station.

Every water system needs to be analyzed in an early stage before starting operations. By doing this critical stations or bottlenecks are detected beforehand and modifications can take place to prevent queues, increasing the flexibility in the system. Moreover, performance measurements are needed to keep the operations under control and detect possible problems that might arise.

Contributions to HNP

The work presented has helped HumanNeeds Project to understand how operations in the Town Center might occur and detect important factors that were not taken into account before. We let them know the importance of the payment and water kiosk stations, increasing the number of servers they initially had in mind. For the Laundry services we informed them that sometimes the capacity might be exceeded so they should limit the number of people in the payment station to prevent people to wait long periods of time without being able to do their laundry.

Furthermore, some improvements can help HNP reduce the queues in the water center and consequently improve the service given to consumers. Top-up cards can decrease the flow of people in the payment station and prevent people to leave the center and go to other water points in the area. On top, it is shown that balancing the flow of people can be the best solution for the Town Center. HumanNeeds Project does not have a lot of money available to invest in new servers so balancing the people during the day will reduce queues in all stations and give a better service to customers. Moreover, management needs to performance measurements to know if the capacity is being exceeded by the demand. If the capacity in the Town Center is topped and HNP cannot invest in new servers, a limitation needs to take place in the payment station. Utilization also provides information on how the distribution of people is during the day, thus, it is a good indicator to determine if the system has sufficient capacity to balance the flow of people.

Concerning the water treatment process, we let the organization know at the beginning of the project the importance of clearing the waste water every day. Failing to empty the system daily will present problems in the operations because the capacity of the treatment process will be exceeded and the center can be flooded. Therefore, the solution was to deliver all the waste water to a school behind the center.

Limitations

Some limitations are present in the analysis since an important part of it is made with estimations. Due to a construction delay the information was gathered through consumer's research and surveys to try to understand the behavior of the people. Thus, information may present some errors and it needs to be verified in the future. Moreover, the arrival times were obtained in a water center in Kibera that has lower capacity so it might not apply to a bigger center. The arrival distribution of the Town Center should be measured to verify the information presented and the service times should be checked to validate the results. Furthermore, the analytical model does not consider multiple services per person. The information about multiple services per person can be introduced in the simulation model, nevertheless, for this analysis it was not considered since it is complex data that has to be measured based on the operations. For the moment, Kibera does not have a center with the same infrastructure and amount of services as the Town Center so the information about multiple services per person cannot be gained from the area. The information concerns the percentage of people that buys multiple services, the services that are combined, and the order in which people use the services in the system, between other several topics. Although the analysis is made with estimations, it helps in the understanding of how the center operates, how people behave, and it can give different scenarios to detect risks and improve service in water systems.

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8 Appendix

Appendix A – Filtration system & water treatment process

Well water for Human consumption

The water system has a capacity of delivering 20,000 L of clean safe water per hour from the borehole. However, this water has to be treated before going to the service stations in the following way:

1) Water is pumped from a well to a 5,000 L pre-filter holding tank.
2) From the holding tank it goes through the Alumina Fluoride treatment system.
3) Then, the water goes to two 5,000 L post-filter holding tanks.
4) Finally, the water is distributed to the Laundry center, Showers, Sinks, Toilets, and Water sales kiosk.

Overall, the system can produce 20 cubic meters (20,000 L) of filtered water per hour.

Recycled water NOT for Human consumption

The water used in the Town Center will be recycled for irrigation purposes in a soccer field and to flush toilets of a school next to the water center that has problems with water supply. The process of the treatment system is as follows:

1) All black and gray water from the Town Center (Laundry center, Showers, Sinks, Toilets, Surface drains) will enter the Septic Tank ($V=32.13m^3$).
2) From the two chamber septic tank the effluent passes through two Anaerobic Filter – AF tanks ($V=59.67m^3$, each Anaerobic tank is divided into 2 smaller tanks—these tanks are filled with plavel (cut up plastic bottles)).
3) Then, the AF tank effluent passes through three Horizontal Roughing Filters – HRF also filled with Plavel ($V_1=6m^3, V_2=7.56m^3, V_3=7.02m^3$).
4) From the HRF's effluent flows into the Flow Equalization Tank – FET (the FET is a two chamber tank: $V=40.8m^3$).
5) After the FET, the effluent is pumped via two pumps up to the two Trickling Filters (5,000 L) filled with more plavel.

6) The effluent then drains back to the FET and then it is pumped up into two Upflow Roughing Filters (5,000 L), filled with stones of different sizes in layers — large stones on the bottom decreasing in size towards the top. Effluent enters the bottom of the tank and filters its way to the top.
7) Subsequently, it may be pumped to five Slow Sand Filters – SSF (same as URF's but filled with sand of different sizes: 5,000 L).
8) Afterwards, from SSF the effluent passes through a Chlorine Bath System – CBS.
9) Next, from the CBS, the now cleaned water (pathogen free) will flow into the underground Recycled Water Storage tank – RWS (V=59.22m^3).
10) From the RWS the now clean water will be distributed to flushing the toilets of the Town center, and delivered to a school next to the center for irrigation of the professional soccer field and to flush the toilets of the school (approximately 3,400 students).

The Slow Sand Filters have a rate of flow between 4,000 and 5,000 L/hour depending on the pump rate. Thus, the treatment process can operate without any problems at a rate of maximum 5,000L per hour.

Appendix B – People carrying jerry cans

In the following pictures it can be observed the people in charge of carrying the jerry cans in slums:

Figure 4 - Children carrying jerry cans

Figure 5 – Families carrying jerry cans

Appendix C – Simulation diagram

The simulation model used is shown below (Figure 6). It has 3 different arrival times' distributions (morning, afternoon, and evening) for each service. Afterwards, all the different demands pass through the payment station and then, they are distributed in different services depending on their choice.

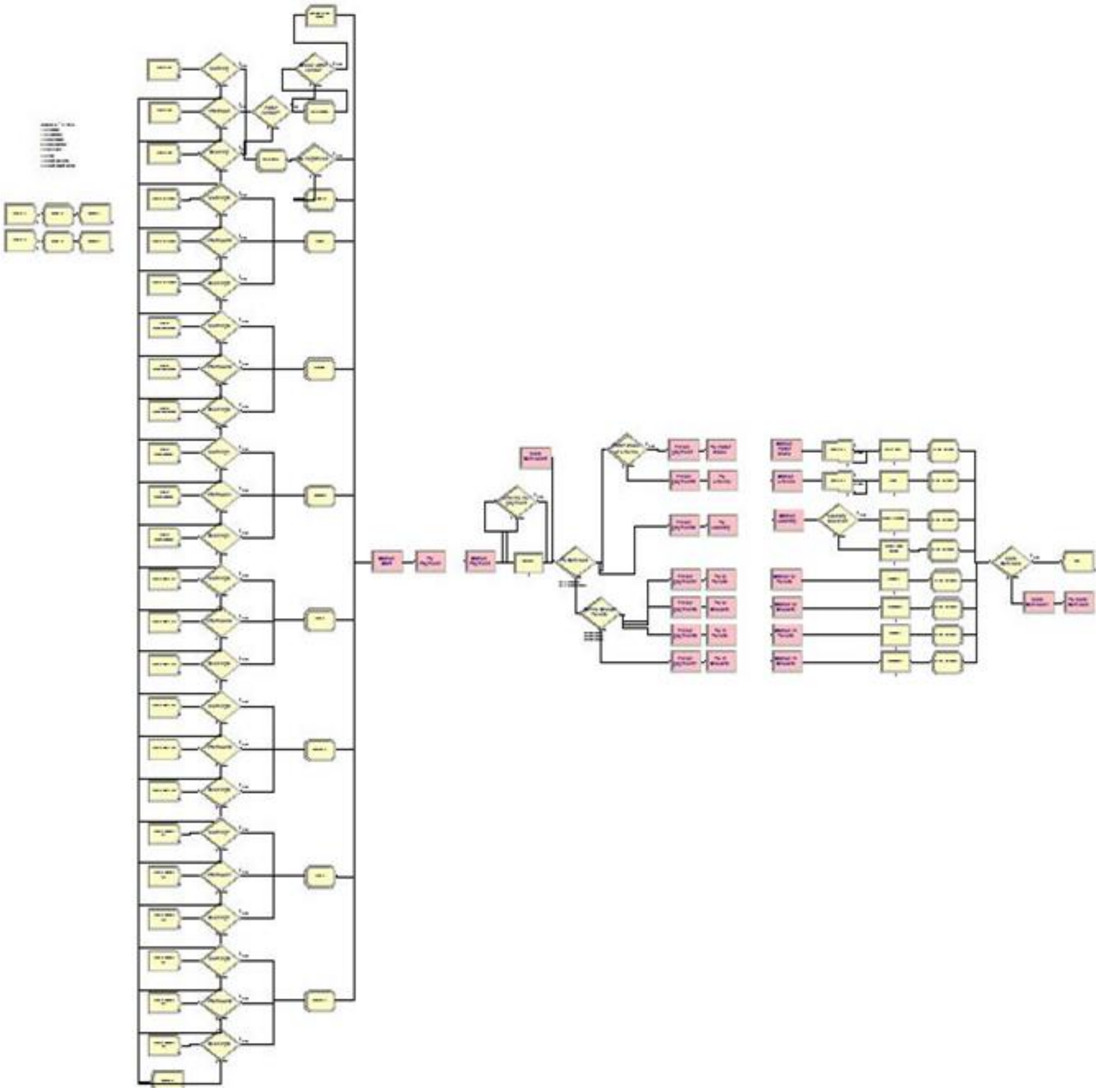


Figure 6 - Simulation model

Appendix D – Warm-up period

To obtain the warm-up period 5 replications were run and the graphs of all the services were plotted as shown:

Water kiosk:

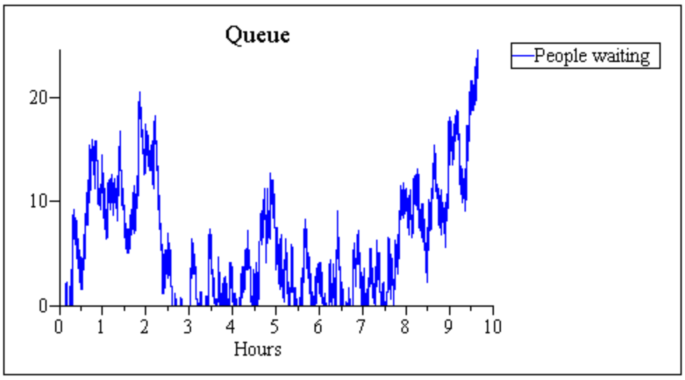


Chart 22- Water Kiosk queue

Lifelink:

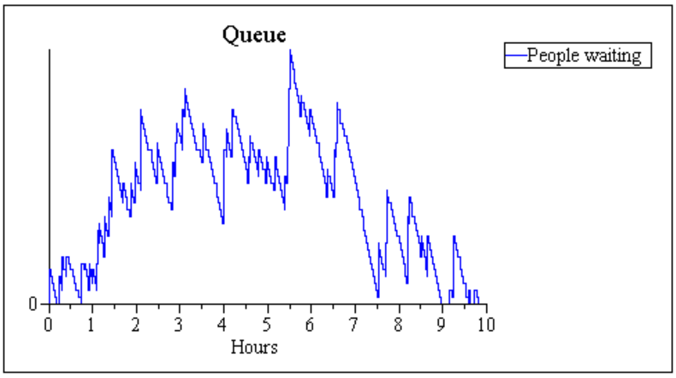


Chart 23 - Lifelink queue

Hand washing:

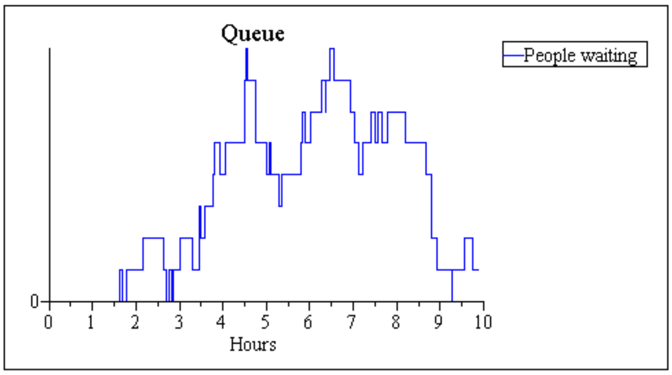


Chart 24 - Hand washing queue

Laundry - Machine:

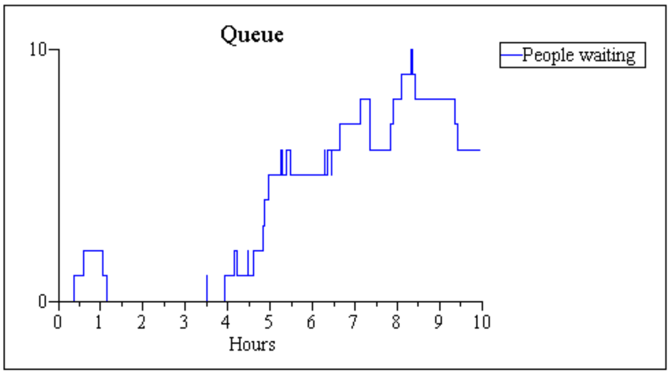


Chart 25 - Washing machine queue

Showers - Men:

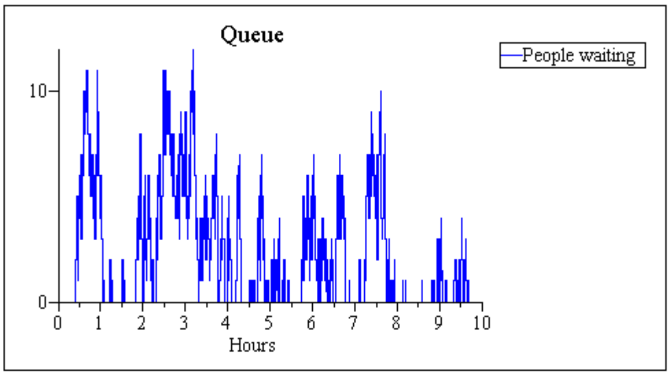


Chart 26 - Showers Men queue

Toilets - Men:

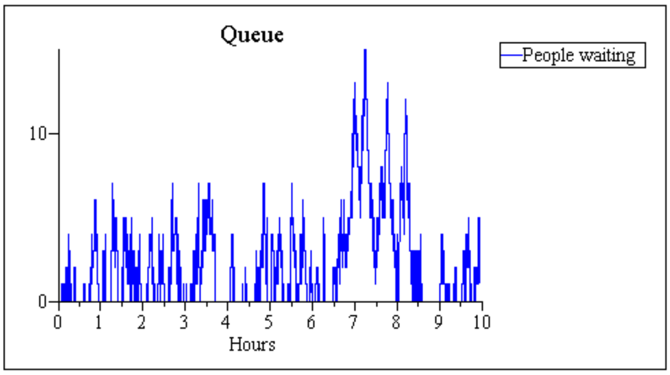


Chart 27 - Toilets Men queue

Payment:

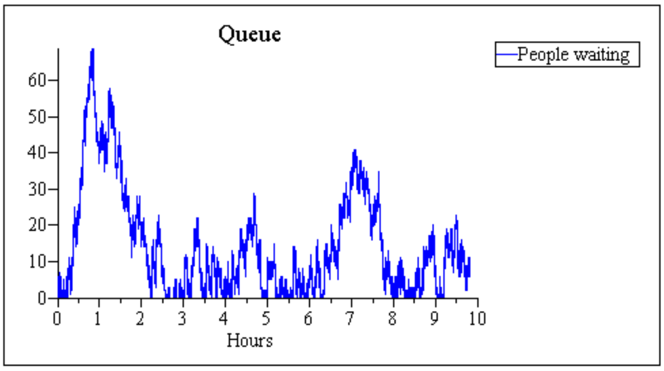


Chart 28 - Payment queue

Showers - Women:

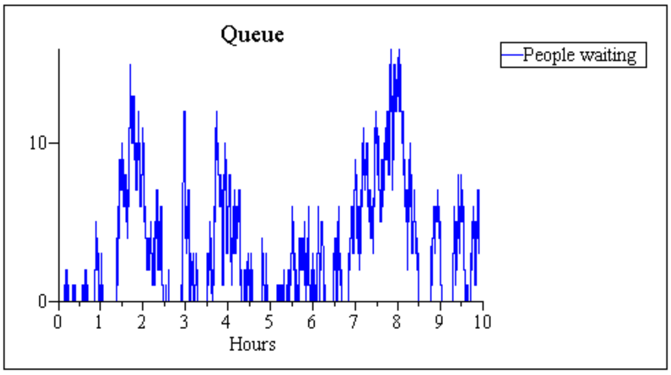


Chart 29 - Showers Women queue

Toilets - Women:

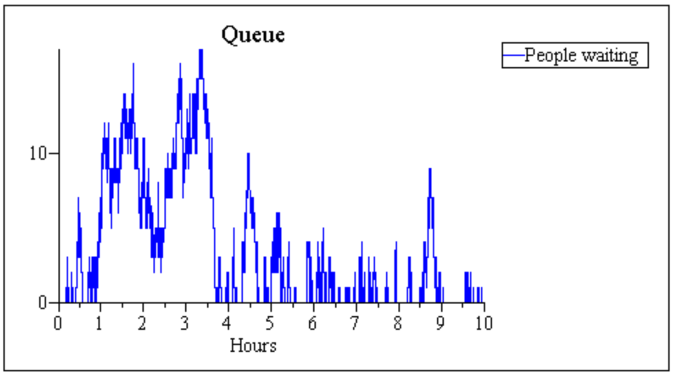


Chart 30 - Toilets Women queue

Based on the previous graphs, it can be appreciated that the Laundry services are the ones that take longer to stabilize. Therefore, multiple simulations were plotted () to see the behavior and define the warm up period.

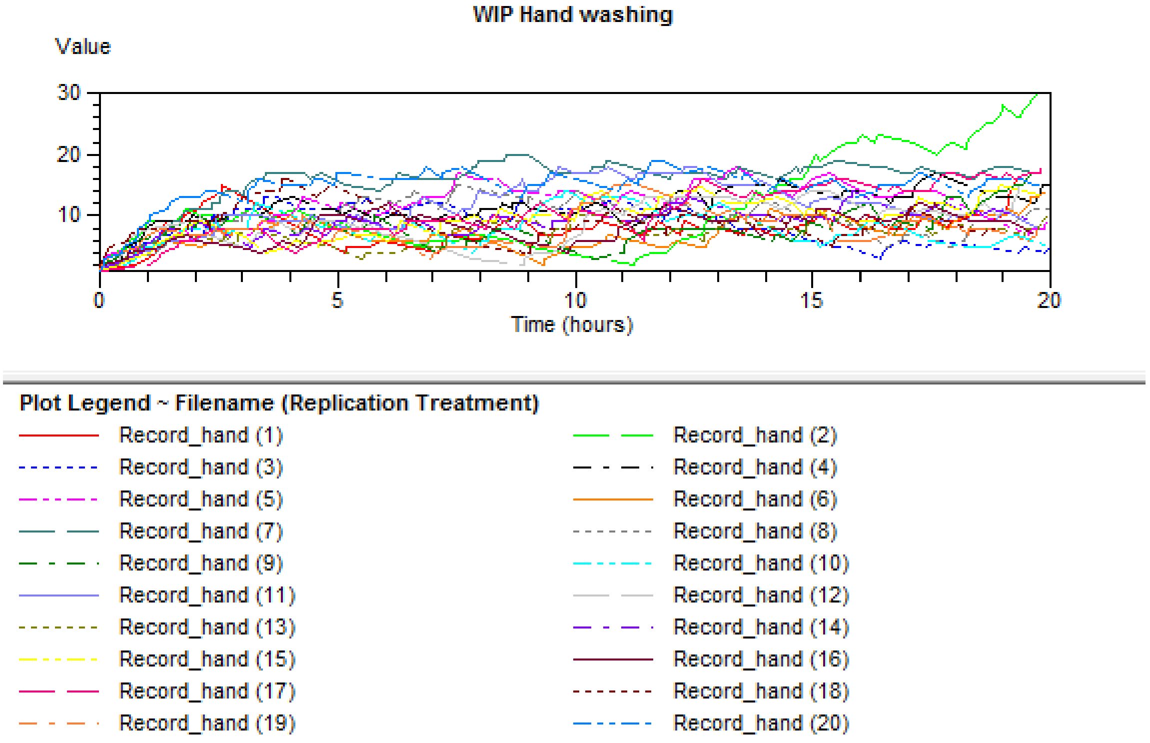


Chart 31 - WIP Hand washing (20 replications)

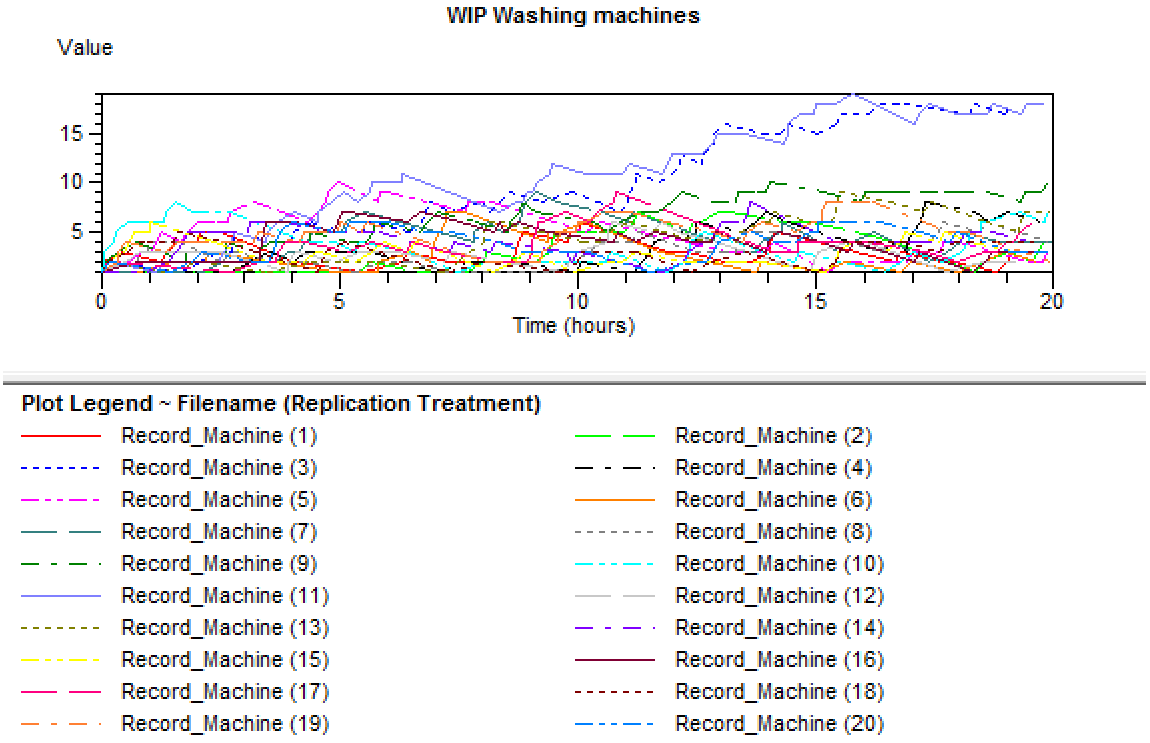
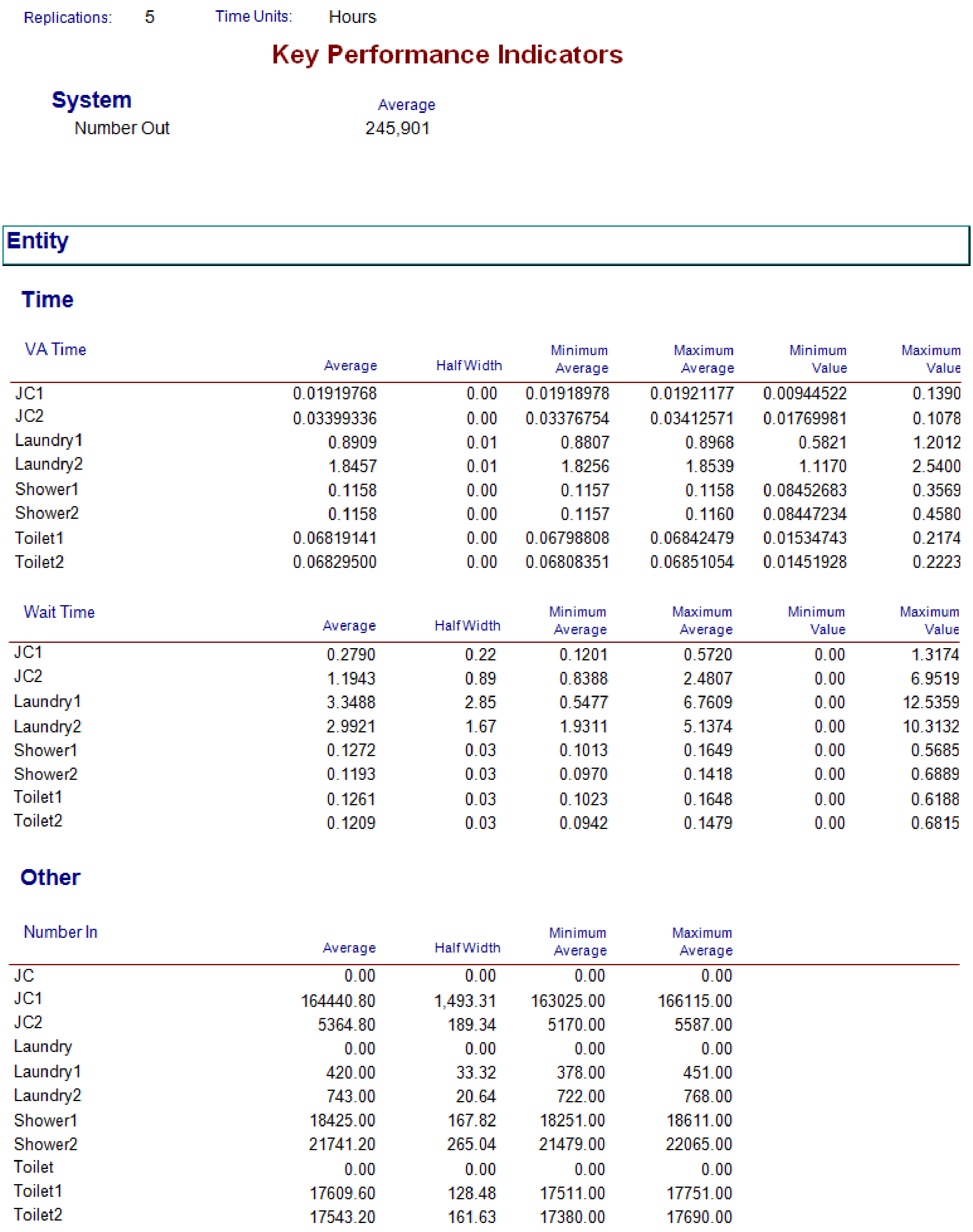


Chart 32 - WIP Washing machines (20 replications)

Appendix E – Simulation results



Replications: 5 Time Units: Hours

Key Performance Indicators

System

	Average
Number Out	245,901

Entity

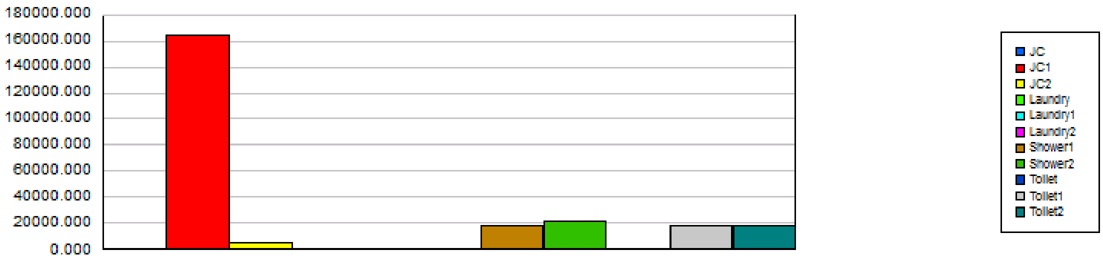
Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
JC1	0.01919768	0.00	0.01918978	0.01921177	0.00944522	0.1390
JC2	0.03399336	0.00	0.03376754	0.03412571	0.01769981	0.1078
Laundry1	0.8909	0.01	0.8807	0.8968	0.5821	1.2012
Laundry2	1.8457	0.01	1.8256	1.8539	1.1170	2.5400
Shower1	0.1158	0.00	0.1157	0.1158	0.08452683	0.3569
Shower2	0.1158	0.00	0.1157	0.1160	0.08447234	0.4580
Toilet1	0.06819141	0.00	0.06798808	0.06842479	0.01534743	0.2174
Toilet2	0.06829500	0.00	0.06808351	0.06851054	0.01451928	0.2223

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
JC1	0.2790	0.22	0.1201	0.5720	0.00	1.3174
JC2	1.1943	0.89	0.8388	2.4807	0.00	6.9519
Laundry1	3.3488	2.85	0.5477	6.7609	0.00	12.5359
Laundry2	2.9921	1.67	1.9311	5.1374	0.00	10.3132
Shower1	0.1272	0.03	0.1013	0.1649	0.00	0.5685
Shower2	0.1193	0.03	0.0970	0.1418	0.00	0.6889
Toilet1	0.1261	0.03	0.1023	0.1648	0.00	0.6188
Toilet2	0.1209	0.03	0.0942	0.1479	0.00	0.6815

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
JC	0.00	0.00	0.00	0.00
JC1	164440.80	1,493.31	163025.00	166115.00
JC2	5364.80	189.34	5170.00	5587.00
Laundry	0.00	0.00	0.00	0.00
Laundry1	420.00	33.32	378.00	451.00
Laundry2	743.00	20.64	722.00	768.00
Shower1	18425.00	167.82	18251.00	18611.00
Shower2	21741.20	265.04	21479.00	22065.00
Toilet	0.00	0.00	0.00	0.00
Toilet1	17609.60	128.48	17511.00	17751.00
Toilet2	17543.20	161.63	17380.00	17690.00



Number Out	Average	Half Width	Minimum Average	Maximum Average
JC	0.00	0.00	0.00	0.00
JC1	164145.80	1,464.83	162959.00	165770.00
JC2	5322.60	159.50	5164.00	5509.00
Laundry	0.00	0.00	0.00	0.00
Laundry1	415.00	30.76	377.00	442.00
Laundry2	728.20	17.89	704.00	741.00
Shower1	18412.40	165.66	18246.00	18599.00
Shower2	21737.20	260.93	21484.00	22054.00
Toilet	0.00	0.00	0.00	0.00
Toilet1	17603.80	128.06	17498.00	17735.00
Toilet2	17536.40	160.70	17395.00	17686.00

Entity

Other

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
JC	0.00	0.00	0.00	0.00	0.00	0.00
JC1	252.99	186.36	117.28	503.84	0.00	1114.00
JC2	34.2410	26.48	23.6364	72.3641	0.00	200.00
Laundry	0.00	0.00	0.00	0.00	0.00	0.00
Laundry1	9.3275	6.76	2.7771	17.5460	0.00	30.0000
Laundry2	18.4685	7.00	13.8648	27.5787	1.0000	47.0000
Shower1	23.4908	3.00	20.8289	27.3012	2.0000	73.0000
Shower2	26.8487	3.04	24.2688	29.2890	2.0000	98.0000
Toilet	0.00	0.00	0.00	0.00	0.00	0.00
Toilet1	18.0584	2.94	15.8263	21.6525	0.00	67.0000
Toilet2	17.5340	2.48	14.9643	20.0599	0.00	71.0000

Queue

Time

Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Laundry Hand washing.Queue	2.9375	1.69	1.8635	5.1108	0.00	10.1365
Laundry Machine.Queue	3.2766	2.87	0.4795	6.7114	0.00	12.5194
Lifelink.Queue	1.1947	0.89	0.8390	2.4815	0.00	6.9519
M_Showers.Queue	0.04479731	0.01	0.03777223	0.05477748	0.00	0.4009
M_Toilets.Queue	0.04397434	0.01	0.03625841	0.05461548	0.00	0.4667
Payment.Queue	0.08252496	0.02	0.06349999	0.1101	0.00	0.4623
W_Showers.Queue	0.03659854	0.01	0.02770047	0.05163860	0.00	0.4890
W_Toilets.Queue	0.03877720	0.01	0.03144980	0.04420835	0.00	0.3351
Water Kiosk.Queue	0.2634	0.22	0.1037	0.5565	0.00	1.2844

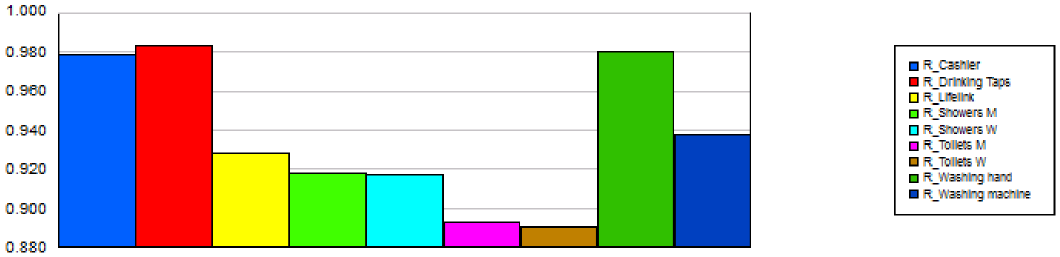
Other

Number Waiting	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Laundry Hand washing.Queue	11.2356	6.82	6.8490	20.0891	0.00	39.0000
Laundry Machine.Queue	7.2422	6.63	0.9296	15.3579	0.00	28.0000
Lifelink.Queue	33.2796	26.46	22.7098	71.3680	0.00	199.00
M_Showers.Queue	4.2341	0.77	3.5359	5.2255	0.00	43.0000
M_Toilets.Queue	3.9722	0.80	3.2536	4.9528	0.00	49.0000
Payment.Queue	45.4881	12.62	34.7357	60.9148	0.00	271.00
W_Showers.Queue	4.0856	1.32	3.0769	5.8388	0.00	62.0000
W_Toilets.Queue	3.4901	0.57	2.8004	4.0083	0.00	33.0000
Water Kiosk.Queue	222.82	186.10	86.6348	473.43	0.00	1098.00

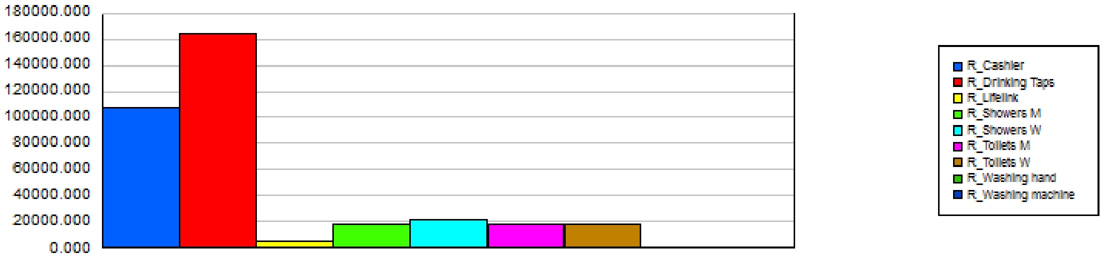
Resource

Usage

Scheduled Utilization	Average	Half Width	Minimum Average	Maximum Average
R_Cashier	0.9785	0.01	0.9735	0.9843
R_Drinking Taps	0.9835	0.01	0.9760	0.9939
R_Lifelink	0.9279	0.03	0.8942	0.9614
R_Showers M	0.9177	0.01	0.9082	0.9269
R_Showers W	0.9168	0.01	0.9074	0.9290
R_Toilets M	0.8926	0.01	0.8843	0.9000
R_Toilets W	0.8901	0.01	0.8810	0.8987
R_Washing hand	0.9803	0.02	0.9536	1.0000
R_Washing machine	0.9377	0.07	0.8445	1.0000



Total Number Seized	Average	Half Width	Minimum Average	Maximum Average
R_Cashier	107373.60	658.14	106674.00	107887.00
R_Drinking Taps	164148.40	1,469.80	162959.00	165782.00
R_Lifelink	5322.60	159.50	5164.00	5509.00
R_Showers M	18413.20	166.40	18246.00	18601.00
R_Showers W	21734.20	258.65	21482.00	22049.00
R_Toilets M	17603.40	127.56	17498.00	17735.00
R_Toilets W	17536.20	160.30	17393.00	17685.00
R_Washing hand	729.00	15.83	708.00	741.00
R_Washing machine	415.40	30.20	378.00	442.00



Appendix F – Maximum peak values

The maximum number of people waiting and how much time they spend on queues were verified and the results are show below:

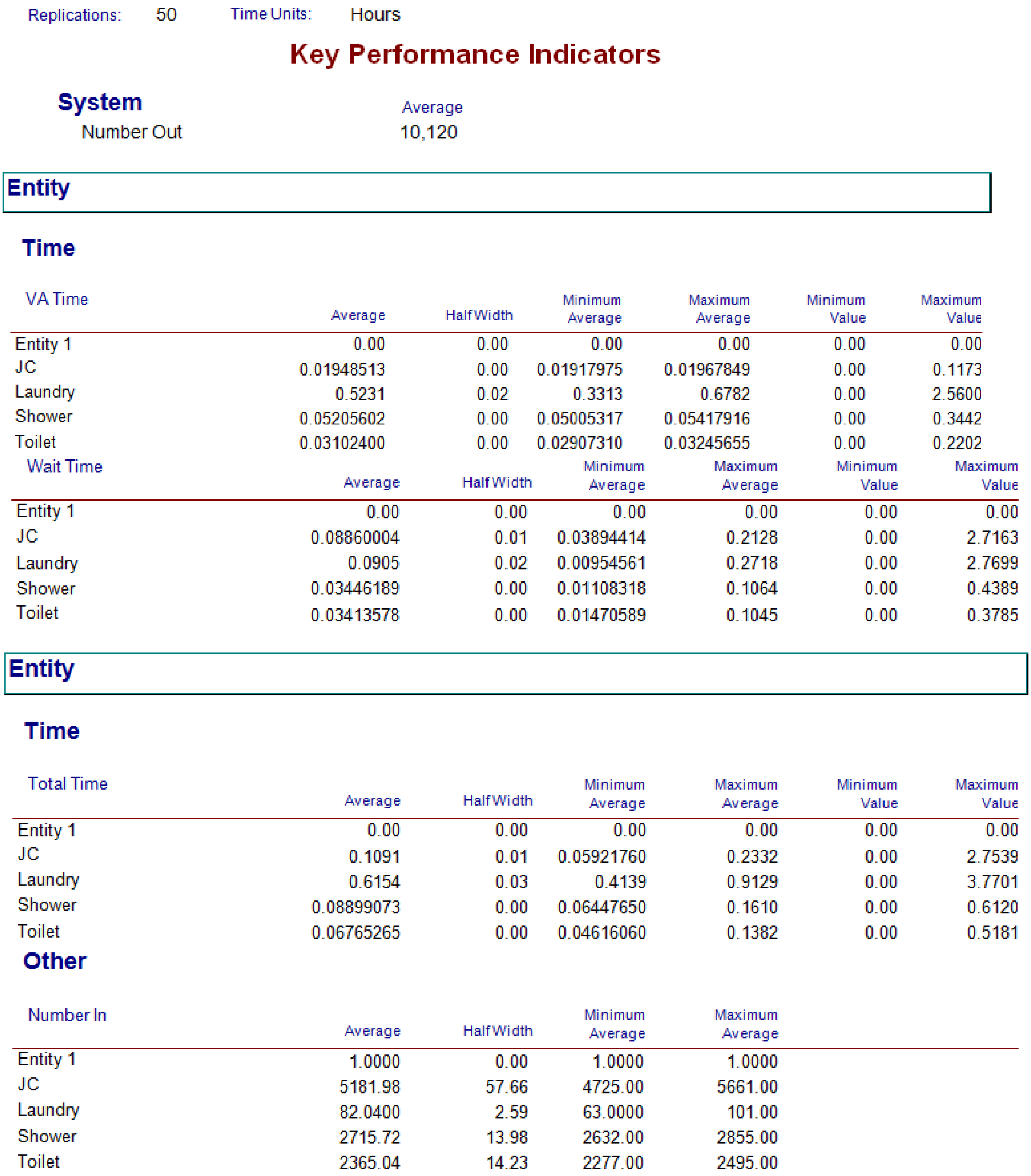
	Morning		***Afternoon***		***Evening***	
	Waiting Time (min)	**# of customers (L)**	**Waiting Time (min)**	**# of customers (L)**	**Waiting Time (min)**	**# of customers (L)**
Payment	19.28	180.00	19.42	166.00	2.86	22.00
Water Kiosk	25.11	73.50	28.18	75.19	5.91	15.41
Lifelink	165.23	22.71	149.42	17.69	81.24	8.73
Shower M	18.41	30.00	13.15	24.00	7.10	12.00
Shower W	20.39	38.00	14.08	26.00	6.08	13.00
Toilet M	15.19	24.00	13.30	21.00	9.19	15.00
Toilet W	17.68	28.00	14.10	23.00	6.11	12.00
	Waiting Time (hr)	**# of customers (L)**	**Waiting Time (hr)**	**# of customers (L)**	**Waiting Time (hr)**	**# of customers (L)**
Hand wash	2.37	10.00	3.10	11.00	2.49	8.00
Machine	2.99	11.00	4.97	12.00	5.52	10.00

Table 21 - Maximum peaks per time period

In the afternoon the maximum peaks are the result of congestion in an earlier stage, which is the reason why they are greater than in the evening in some cases.

Appendix G - Simulations per period of time

Morning:



Replications: 50 Time Units: Hours

Key Performance Indicators

System

	Average
Number Out	10,120

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	0.00	0.00	0.00	0.00	0.00
JC	0.01948513	0.00	0.01917975	0.01967849	0.00	0.1173
Laundry	0.5231	0.02	0.3313	0.6782	0.00	2.5600
Shower	0.05205602	0.00	0.05005317	0.05417916	0.00	0.3442
Toilet	0.03102400	0.00	0.02907310	0.03245655	0.00	0.2202

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	0.00	0.00	0.00	0.00	0.00
JC	0.08860004	0.01	0.03894414	0.2128	0.00	2.7163
Laundry	0.0905	0.02	0.00954561	0.2718	0.00	2.7699
Shower	0.03446189	0.00	0.01108318	0.1064	0.00	0.4389
Toilet	0.03413578	0.00	0.01470589	0.1045	0.00	0.3785

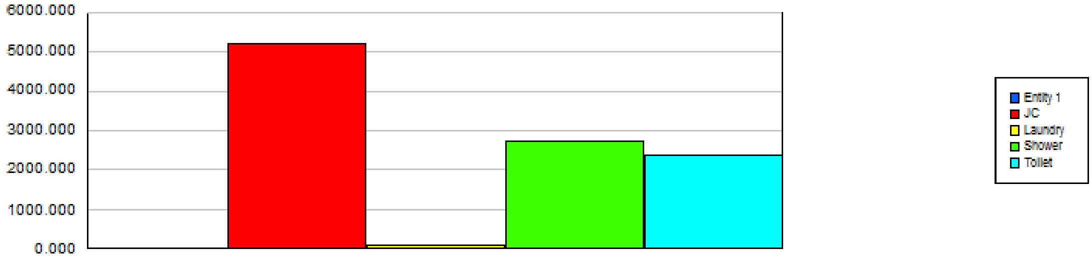
Entity

Time

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	0.00	0.00	0.00	0.00	0.00
JC	0.1091	0.01	0.05921760	0.2332	0.00	2.7539
Laundry	0.6154	0.03	0.4139	0.9129	0.00	3.7701
Shower	0.08899073	0.00	0.06447650	0.1610	0.00	0.6120
Toilet	0.06765265	0.00	0.04616060	0.1382	0.00	0.5181

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
Entity 1	1.0000	0.00	1.0000	1.0000
JC	5181.98	57.66	4725.00	5661.00
Laundry	82.0400	2.59	63.0000	101.00
Shower	2715.72	13.98	2632.00	2855.00
Toilet	2365.04	14.23	2277.00	2495.00



Number Out	Average	Half Width	Minimum Average	Maximum Average
Entity 1	1.0000	0.00	1.0000	1.0000
JC	5045.86	40.72	4666.00	5297.00
Laundry	67.6000	2.03	51.0000	85.0000
Shower	2671.36	14.02	2579.00	2818.00
Toilet	2334.64	13.52	2234.00	2453.00

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	0.00	0.00	0.00	0.00	1.0000
JC	96.9886	11.06	49.7577	211.91	0.00	451.00
Laundry	9.9334	0.65	5.9429	17.8897	0.00	26.0000
Shower	40.5631	2.30	28.8835	74.5505	0.00	113.00
Toilet	26.8538	1.84	18.8601	56.8026	0.00	80.0000

Queue

Time

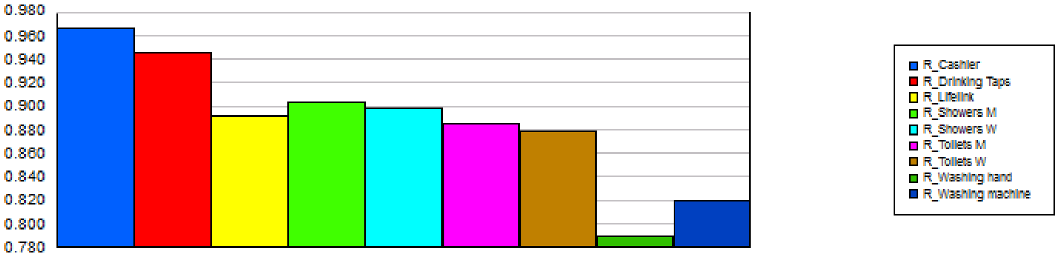
Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Laundry Hand washing.Queue	0.2580	0.07	0.00	0.9910	0.00	2.3659
Laundry Machine.Queue	0.4541	0.10	0.00	1.4299	0.00	2.9928
Lifelink.Queue	0.4909	0.09	0.1291	1.5028	0.00	2.7539
M_Showers.Queue	0.03839682	0.01	0.01175368	0.1081	0.00	0.3069
M_Toilets.Queue	0.03409844	0.00	0.01343732	0.08918265	0.00	0.2531
Payment.Queue	0.04119044	0.01	0.01312509	0.2135	0.00	0.3213
W_Showers.Queue	0.03393689	0.01	0.00669927	0.1542	0.00	0.3399
W_Toilets.Queue	0.03574579	0.01	0.01346951	0.1190	0.00	0.2947
Water Kiosk.Queue	0.06823010	0.01	0.01664049	0.1855	0.00	0.4185

Other

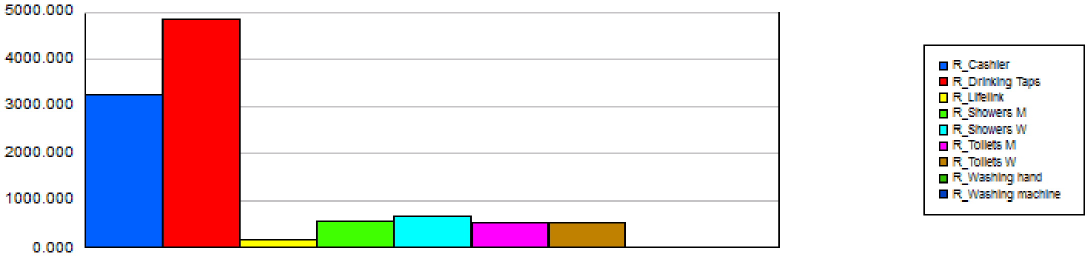
Number Waiting	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Laundry Hand washing.Queue	1.1859	0.33	0.00	4.8460	0.00	10.0000
Laundry Machine.Queue	1.2662	0.36	0.00	4.8215	0.00	11.0000
Lifelink.Queue	15.9674	3.55	2.2975	67.2472	0.00	104.00
M_Showers.Queue	3.6523	0.69	1.0500	10.5813	0.00	30.0000
M_Toilets.Queue	3.0893	0.44	1.1766	8.1695	0.00	24.0000
Payment.Queue	22.6433	4.89	6.9300	118.43	0.00	180.00
W_Showers.Queue	3.8144	0.94	0.6672	17.9960	0.00	38.0000
W_Toilets.Queue	3.2149	0.50	1.1427	12.0142	0.00	28.0000
Water Kiosk.Queue	57.1830	10.31	12.3583	167.78	0.00	391.00

Usage

Scheduled Utilization	Average	Half Width	Minimum Average	Maximum Average
R_Cashier	0.9660	0.01	0.9182	0.9979
R_Drinking Taps	0.9449	0.01	0.8663	0.9944
R_Lifelink	0.8920	0.03	0.5769	0.9991
R_Showers M	0.9034	0.01	0.8602	0.9752
R_Showers W	0.8988	0.01	0.8037	0.9574
R_Toilets M	0.8849	0.01	0.8045	0.9620
R_Toilets W	0.8782	0.01	0.7902	0.9818
R_Washing hand	0.7889	0.03	0.5308	0.9319
R_Washing machine	0.8193	0.05	0.3598	0.9943



Total Number Seized	Average	Half Width	Minimum Average	Maximum Average
R_Cashier	3258.40	16.10	3113.00	3382.00
R_Drinking Taps	4855.52	41.15	4456.00	5128.00
R_Lifelink	157.40	4.94	104.00	182.00
R_Showers M	556.92	5.05	528.00	595.00
R_Showers W	654.20	6.82	587.00	695.00
R_Toilets M	530.34	5.67	492.00	583.00
R_Toilets W	527.82	6.66	480.00	589.00
R_Washing hand	19.9000	0.60	14.0000	23.0000
R_Washing machine	10.6400	0.57	5.0000	13.0000



Afternoon:

Replications: 50 Time Units: Hours

Key Performance Indicators

System

	Average
Number Out	7,491

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	0.00	0.00	0.00	0.00	0.00
JC	0.01441890	0.00	0.01382952	0.01500955	0.00	0.1043
Laundry	0.5082	0.02	0.3007	0.6735	0.00	2.5664
Shower	0.02700914	0.00	0.02402009	0.02972568	0.00	0.3261
Toilet	0.01579442	0.00	0.01332747	0.01785884	0.00	0.2373

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	0.00	0.00	0.00	0.00	0.00
JC	0.03223475	0.01	0.00329864	0.1102	0.00	3.4230
Laundry	0.2608	0.06	0.00723873	1.0055	0.00	4.1395
Shower	0.00287428	0.00	0.00016596	0.01518252	0.00	0.4000
Toilet	0.00279996	0.00	0.00012583	0.01406624	0.00	0.3998

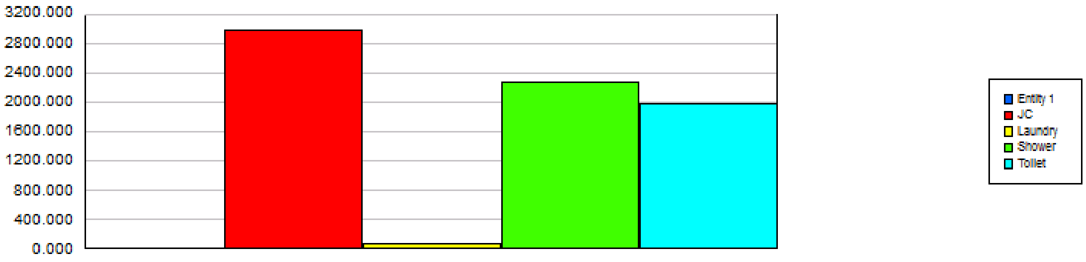
Entity

Time

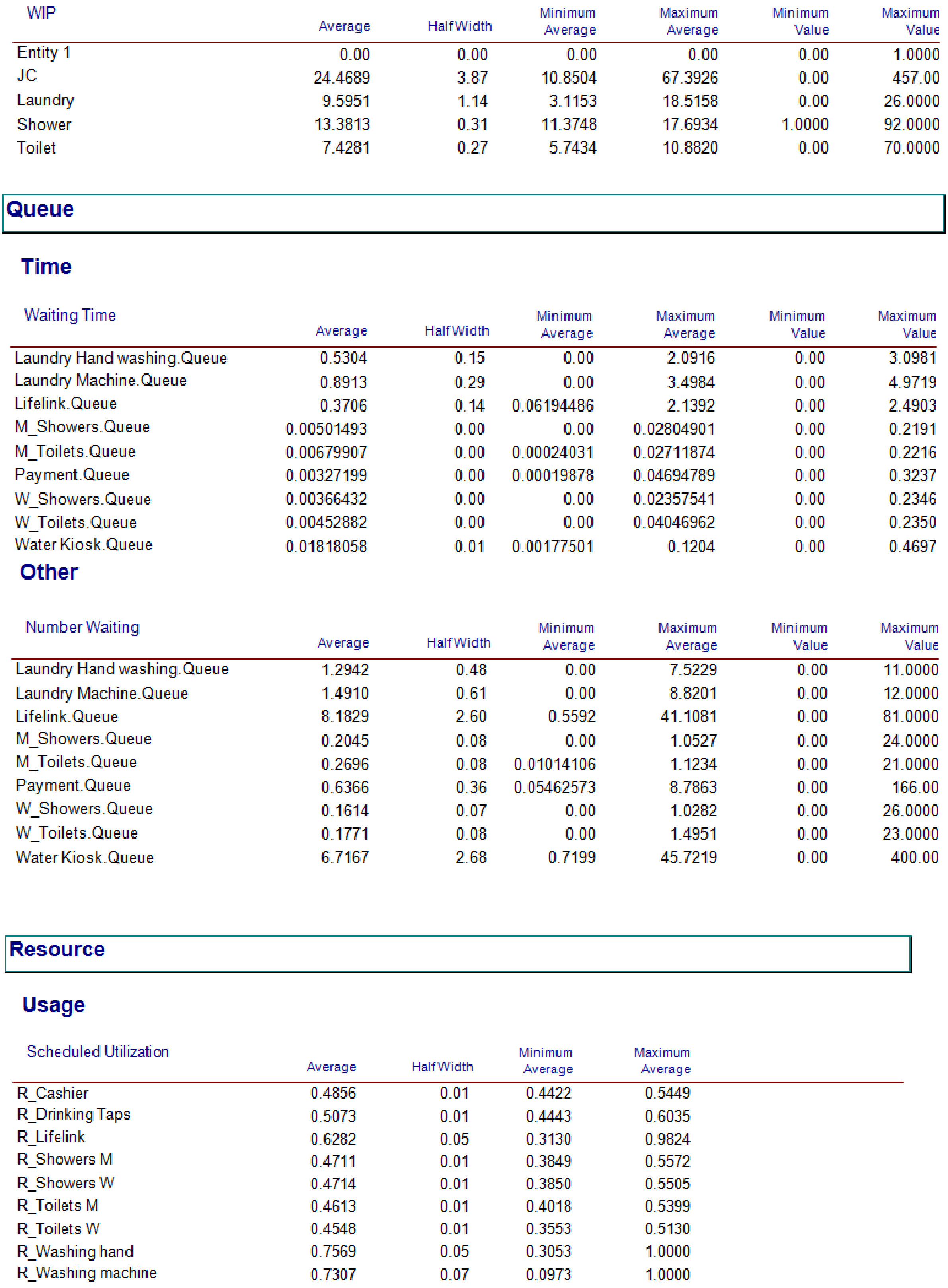
Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	0.00	0.00	0.00	0.00	0.00
JC	0.04741625	0.01	0.01821835	0.1260	0.00	3.4631
Laundry	0.7707	0.07	0.3150	1.6699	0.00	5.1767
Shower	0.03116243	0.00	0.02581922	0.04502638	0.00	0.5818
Toilet	0.01985590	0.00	0.01457285	0.03263974	0.00	0.5267

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
Entity 1	2.0000	0.00	2.0000	2.0000
JC	2989.00	37.68	2742.00	3315.00
Laundry	65.2600	2.06	47.0000	78.0000
Shower	2262.14	15.17	2130.00	2390.00
Toilet	1985.22	11.23	1860.00	2111.00



Number Out	Average	Half Width	Minimum Average	Maximum Average
Entity 1	2.0000	0.00	2.0000	2.0000
JC	3113.02	48.74	2829.00	3619.00
Laundry	72.8000	2.01	56.0000	85.0000
Shower	2294.26	15.94	2163.00	2423.00
Toilet	2008.80	12.16	1874.00	2127.00



WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	0.00	0.00	0.00	0.00	1.0000
JC	24.4689	3.87	10.8504	67.3926	0.00	457.00
Laundry	9.5951	1.14	3.1153	18.5158	0.00	26.0000
Shower	13.3813	0.31	11.3748	17.6934	1.0000	92.0000
Toilet	7.4281	0.27	5.7434	10.8820	0.00	70.0000

Queue

Time

Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Laundry Hand washing.Queue	0.5304	0.15	0.00	2.0916	0.00	3.0981
Laundry Machine.Queue	0.8913	0.29	0.00	3.4984	0.00	4.9719
Lifelink.Queue	0.3706	0.14	0.06194486	2.1392	0.00	2.4903
M_Showers.Queue	0.00501493	0.00	0.00	0.02804901	0.00	0.2191
M_Toilets.Queue	0.00679907	0.00	0.00024031	0.02711874	0.00	0.2216
Payment.Queue	0.00327199	0.00	0.00019878	0.04694789	0.00	0.3237
W_Showers.Queue	0.00366432	0.00	0.00	0.02357541	0.00	0.2346
W_Toilets.Queue	0.00452882	0.00	0.00	0.04046962	0.00	0.2350
Water Kiosk.Queue	0.01818058	0.01	0.00177501	0.1204	0.00	0.4697

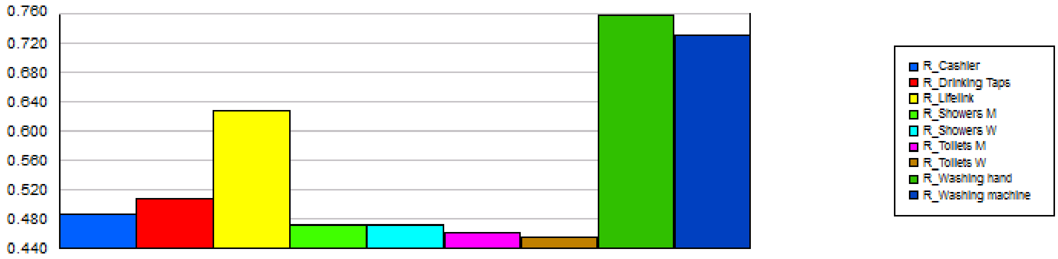
Other

Number Waiting	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Laundry Hand washing.Queue	1.2942	0.48	0.00	7.5229	0.00	11.0000
Laundry Machine.Queue	1.4910	0.61	0.00	8.8201	0.00	12.0000
Lifelink.Queue	8.1829	2.60	0.5592	41.1081	0.00	81.0000
M_Showers.Queue	0.2045	0.08	0.00	1.0527	0.00	24.0000
M_Toilets.Queue	0.2696	0.08	0.01014106	1.1234	0.00	21.0000
Payment.Queue	0.6366	0.36	0.05462573	8.7863	0.00	166.00
W_Showers.Queue	0.1614	0.07	0.00	1.0282	0.00	26.0000
W_Toilets.Queue	0.1771	0.08	0.00	1.4951	0.00	23.0000
Water Kiosk.Queue	6.7167	2.68	0.7199	45.7219	0.00	400.00

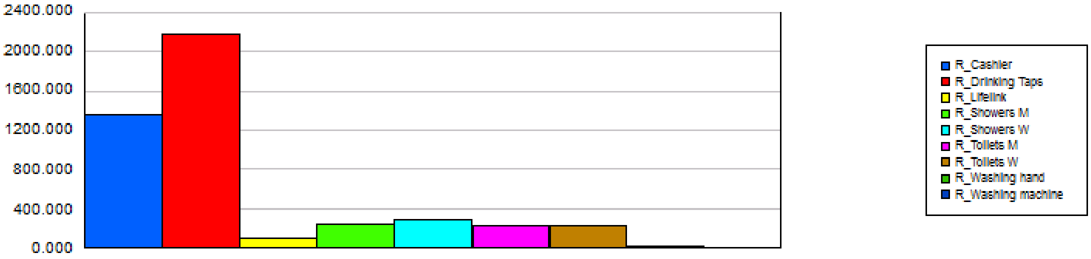
Resource

Usage

Scheduled Utilization	Average	Half Width	Minimum Average	Maximum Average
R_Cashier	0.4856	0.01	0.4422	0.5449
R_Drinking Taps	0.5073	0.01	0.4443	0.6035
R_Lifelink	0.6282	0.05	0.3130	0.9824
R_Showers M	0.4711	0.01	0.3849	0.5572
R_Showers W	0.4714	0.01	0.3850	0.5505
R_Toilets M	0.4613	0.01	0.4018	0.5399
R_Toilets W	0.4548	0.01	0.3553	0.5130
R_Washing hand	0.7569	0.05	0.3053	1.0000
R_Washing machine	0.7307	0.07	0.0973	1.0000



Total Number Seized	Average	Half Width	Minimum Average	Maximum Average
R_Cashier	1354.10	12.88	1252.00	1499.00
R_Drinking Taps	2169.50	46.23	1911.00	2609.00
R_Lifelink	92.3400	8.00	45.0000	149.00
R_Showers M	236.94	5.04	195.00	277.00
R_Showers W	279.74	5.51	223.00	319.00
R_Toilets M	227.62	4.40	201.00	269.00
R_Toilets W	223.46	5.10	184.00	256.00
R_Washing hand	11.7800	1.10	5.0000	19.0000
R_Washing machine	7.1200	0.73	1.0000	11.0000



Evening:

Replications: 50 Time Units: Hours

Key Performance Indicators

System

	Average
Number Out	8,624

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	0.00	0.00	0.00	0.00	0.00
JC	0.01412972	0.00	0.01355426	0.01454192	0.00	0.1073
Laundry	0.5271	0.03	0.2729	0.7850	0.00	2.6166
Shower	0.03789978	0.00	0.03567649	0.04193046	0.00	0.3493
Toilet	0.02262560	0.00	0.02112602	0.02431954	0.00	0.2543

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	0.00	0.00	0.00	0.00	0.00
JC	0.01089243	0.00	0.00415013	0.02013412	0.00	1.3540
Laundry	0.1409	0.05	0.00006842	0.6694	0.00	5.5227
Shower	0.00155218	0.00	0.00068630	0.00426643	0.00	0.1372
Toilet	0.00240935	0.00	0.00139981	0.00687196	0.00	0.1542

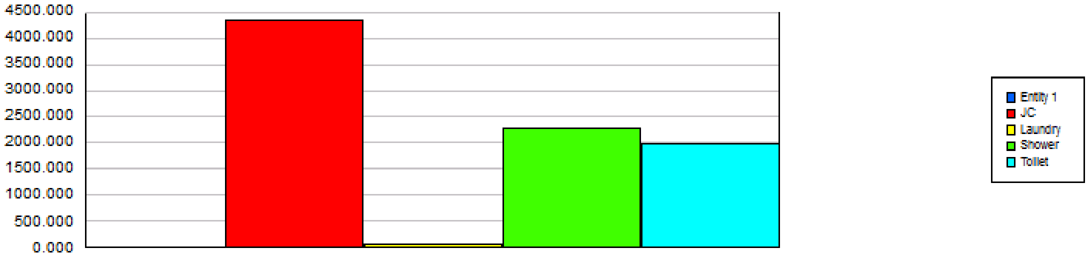
Entity

Time

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	0.00	0.00	0.00	0.00	0.00
JC	0.02577428	0.00	0.01856625	0.03496130	0.00	1.3754
Laundry	0.6698	0.07	0.2739	1.3279	0.00	6.5031
Shower	0.04125442	0.00	0.03893241	0.04813673	0.00	0.3548
Toilet	0.02684717	0.00	0.02448636	0.03305928	0.00	0.2691

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
Entity 1	1.0000	0.00	1.0000	1.0000
JC	4334.38	44.65	3847.00	4688.00
Laundry	63.4200	2.59	48.0000	93.0000
Shower	2266.28	14.36	2169.00	2384.00
Toilet	1982.70	14.00	1869.00	2075.00



Number Out	Average	Half Width	Minimum Average	Maximum Average
Entity 1	1.0000	0.00	1.0000	1.0000
JC	4322.96	43.76	3847.00	4689.00
Laundry	61.3800	2.26	46.0000	86.0000
Shower	2260.26	14.29	2160.00	2371.00
Toilet	1978.64	14.00	1866.00	2078.00

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	0.00	0.00	0.00	0.00	1.0000
JC	22.5196	1.05	14.2869	31.1208	0.00	121.00
Laundry	8.4030	0.82	4.0749	17.7513	1.0000	25.0000
Shower	18.7320	0.25	17.2679	22.1748	2.0000	42.0000
Toilet	10.6754	0.22	9.4769	13.6807	0.00	30.0000

Queue

Time

Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Laundry Hand washing.Queue	0.2234	0.11	0.00	1.9972	0.00	2.4886
Laundry Machine.Queue	0.5863	0.24	0.00	3.9425	0.00	5.5227
Lifelink.Queue	0.2068	0.03	0.07801413	0.5930	0.00	1.3540
M_Showers.Queue	0.00237189	0.00	0.00043916	0.00695358	0.00	0.1184
M_Toilets.Queue	0.00551509	0.00	0.00129520	0.02616460	0.00	0.1532
Payment.Queue	0.00234522	0.00	0.00119293	0.00507822	0.00	0.04769550
W_Showers.Queue	0.00247201	0.00	0.00008065	0.01183064	0.00	0.1014
W_Toilets.Queue	0.00466284	0.00	0.00118742	0.01363124	0.00	0.1018
Water Kiosk.Queue	0.00818059	0.00	0.00427601	0.01236179	0.00	0.0985

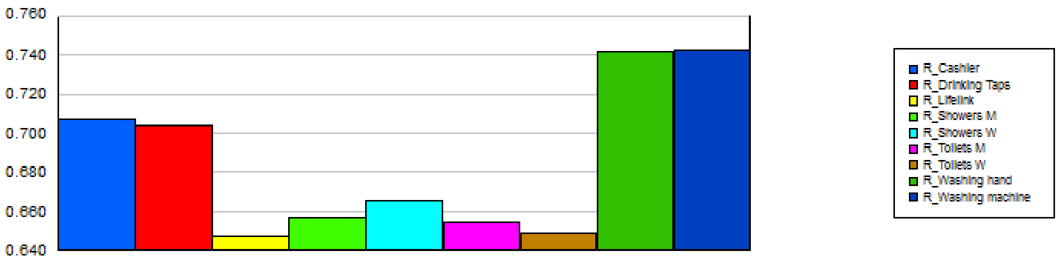
Other

Number Waiting	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Laundry Hand washing.Queue	0.7346	0.37	0.00	5.8463	0.00	8.0000
Laundry Machine.Queue	0.9184	0.42	0.00	7.7709	0.00	10.0000
Lifelink.Queue	4.3910	0.87	0.7779	12.5711	0.00	40.0000
M_Showers.Queue	0.1634	0.03	0.02924837	0.5577	0.00	12.0000
M_Toilets.Queue	0.3678	0.10	0.08211590	1.9018	0.00	15.0000
Payment.Queue	0.9284	0.08	0.4653	2.0059	0.00	22.0000
W_Showers.Queue	0.2030	0.06	0.00609713	1.0458	0.00	13.0000
W_Toilets.Queue	0.3064	0.05	0.07266980	0.9378	0.00	12.0000
Water Kiosk.Queue	4.9800	0.36	2.2509	8.1341	0.00	82.0000

Resource

Usage

Scheduled Utilization	Average	Half Width	Minimum Average	Maximum Average
R_Cashier	0.7073	0.01	0.6551	0.7523
R_Drinking Taps	0.7043	0.01	0.6149	0.7769
R_Lifelink	0.6470	0.04	0.3400	0.9776
R_Showers M	0.6567	0.01	0.5734	0.7748
R_Showers W	0.6653	0.01	0.5988	0.7487
R_Toilets M	0.6543	0.01	0.5864	0.7262
R_Toilets W	0.6490	0.01	0.5735	0.7464
R_Washing hand	0.7419	0.05	0.3826	1.0000
R_Washing machine	0.7422	0.06	0.1339	1.0000



Total Number Seized	Average	Half Width	Minimum Average	Maximum Average
R_Cashier	1976.00	11.74	1870.00	2055.00
R_Drinking Taps	3015.66	41.20	2632.00	3290.00
R_Lifelink	95.9400	5.98	45.0000	147.00
R_Showers M	336.72	5.95	289.00	406.00
R_Showers W	401.76	5.07	366.00	442.00
R_Toilets M	326.02	4.31	286.00	363.00
R_Toilets W	322.02	5.34	287.00	363.00
R_Washing hand	13.8200	0.91	5.0000	20.0000
R_Washing machine	7.5000	0.59	1.0000	10.0000