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To What Extent Would Operational Restructuring Through Connecting Market Participants Streamline the Informal Recycling Industry in Urban India?

Peter W. Hjemdahl
University of Pennsylvania, peterhjem@gmail.com

Svanika Balasubramanian
University of Pennsylvania, svanikab@gmail.com

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Abstract

As the economies of developing countries grow, the waste production in these nations also increases proportionally. However, local governments are constrained by both the lack of adequate funds and a lack of skilled human capital, and are thus unable to build necessary waste management infrastructure. The majority of waste produced in these urban centres end up untreated in landfills, proving to be a social and environmental danger. A small portion of this refuse is handled by a vibrant informal recycling industry that is unable to scale given myriad inefficiencies. We propose the implementation of a tech-enabled marketplace platform to consolidate the supply chain by more efficiently connecting the relevant stakeholders. This model has the potential of increasing the volume of waste processed by scrap dealers (kabadiwalas) and increasing their unit margins by taking advantage of economies of scale, cumulatively doubling their income and simultaneously diverting waste away from landfills.

Keywords

optimization, recycling, waste management, informal, india, mumbai, solid waste, plastic, paper

Disciplines

Business Analytics | Entrepreneurial and Small Business Operations | Environmental Studies | Infrastructure | International Business | Operations and Supply Chain Management | Technology and Innovation | Urban Studies and Planning

Comments

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By

Svanika Balasubramanian (svanikab@gmail.com)

Peter Wang Hjemdahl (peterhjem@gmail.com)

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Faculty Advisor:

Senthil Veeraraghavan

Professor of Operations, Information and Decisions

THE WHARTON SCHOOL, UNIVERSITY OF PENNSYLVANIA

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ABSTRACT

As the economies of developing countries grow, the waste production in these nations also increases proportionally. However, local governments are constrained by both the lack of adequate funds and a lack of skilled human capital, and are thus unable to build necessary waste management infrastructure. The majority of waste produced in these urban centres end up untreated in landfills, proving to be a social and environmental danger. A small portion of this refuse is handled by a vibrant informal recycling industry that is unable to scale given myriad inefficiencies. We propose the implementation of a tech-enabled marketplace platform to consolidate the supply chain by more efficiently connecting the relevant stakeholders. This model has the potential of increasing the volume of waste processed by scrap dealers (kabadiwalas) and increasing their unit margins by taking advantage of economies of scale, cumulatively doubling their income and simultaneously diverting waste away from landfills.

Key words: Optimization, Recycling, Waste Management

INTRODUCTION

Introduction to the Research Area

According to World Bank estimates, the world's cities generated around 1.3 billion tonnes of solid waste in 2012. Other recent surveys by the United Nations Environment Program (UNEP) indicate that around 300 million tonnes of plastic waste is produced every year worldwide. Nearly ten percent of this waste is dumped into the oceans, imparting extreme damage to marine ecosystems. The remaining vast majority of the untreated trash finds its way to overfilled landfills where it is left untouched for decades, or incinerated in an environmentally unsustainable manner. With global waste generation expected to *double* by the year 2025 to 2.2 billion tonnes annually, there is an urgent need for more efficient management, and disposal, of our collective refuse.

This issue is especially imperative in developing countries where globalization has rapidly increased per capita consumption, and subsequently, waste production. Municipalities in low and middle income countries are burdened by the demands of urbanization and tend to be ill-equipped, both on financial and human capital grounds, to provide the infrastructure necessary for sustainable development. Disorganized landfills and open dumps encroach onto neighboring residential areas, predominantly poor slum dwellings, while also polluting the surrounding land and water bodies. In 2017, a fatal landslide at a landfill outside the Ethiopian capital Addis Ababa left over 113 people dead. In 2016, a similar landslide in Mozambique killed 13 people. Aside from such immediate concerns of crumbling landfills, more long-term environmental concerns also remain. A study conducted on the Perungudi landfill site in Chennai, India showed that it contributed to a three-fold increase in the contamination of soil and groundwater in just 3 years (Prasanna et al, 2016). Mistreatment of urban waste have several adverse social, environmental, and health consequences that limit the growth potential of cities across the world. With governments being unable, or unwilling, to rise to this urgent need we turn to the recycling private sector for a better solution.

Informal Recycling in Urban Centres

In the large urban centres of the developing world, there exists a vibrant informal ecosystem that connects the waste generated (either by directly collecting material from waste generators such as households, or by sourcing from landfills) to recyclers and manufacturers. In 2014, the World Bank estimated that up to 2% of urban populations in low and middle income countries work in the informal waste sector – this means that more than 15 million people scavenge, sort, and process recyclable materials such as plastic, metal, and paper around the world on a daily basis. However, despite the importance of this sector from both economic and environmental angles, the industry has remained relatively stagnant for the past few decades with limited disruption or adoption of enabling technologies. Startup innovation also remains relatively stagnant in the sector given a) the lackluster appeal of working with waste and b) a convoluted and chaotic supply chain with multiple barriers to entry. This has created market inefficiencies that restrict the sector from realizing its true potential in terms of economic empowerment and environmental impact. The following section provides a more detailed overview of the informal recycling sector in urban India, where the majority of our on-the-ground research was actively focused.

RESEARCH SCOPE AND HYPOTHESIS

Geographic Scope of the Thesis

For the purposes of this thesis, we chose to focus our attention on a subset of the informal recycling sector of emerging economies. Urban India was chosen for three key reasons. Firstly, the problem manifests itself at an enormous scale in the country which provides ample space for intervention and research. As both population and economic prosperity in India grow alongside manufacturing output, so does the waste generated by the country. After China and the United States, India leads the world in waste creation. For instance, even by conservative estimates, the 400 million citizens who live in urban India produce 62 million tonnes of waste every single day. Of this, 45 million tonnes are left untreated in landfills, leading to long term concerns over pollution-related health issues and environmental degradation. A solution that is proven to work in as complex and unregulated an environment as India can be easily adapted to other less complicated regions. Second, both investigators for this thesis have a familiarity with the Indian society and have already spent an extensive amount of time working with urban India's informal recycling sector. We are able to approach the research with some level of foundational knowledge that allows us to better design our field activities. Lastly, we are also able to access, and leverage, a vast network of collaborators on the ground for conducting further research. Of note are four organizations that have proved immensely useful. First, the Green Communities Foundation (GCF), a non-profit venture that offers accessible, affordable, and efficient solid waste management solutions to bulk waste generators such as large housing societies and corporate offices, was instrumental in gaining access to household consumers and the start point of the value chain (as discussed in the following sections). Second, RaddiConnect, a waste management company that provides doorstep waste pick-up services for offices, institutions, households, and schools, was able to give us access to its network of 150 kabadiwalas (scrap dealers) who were the focus of our research. Third, Acorn Foundation, a non-profit collective that aims to empower impoverished waste pickers, helped us gain better insight into Mumbai's informal industry by connecting us with various supply chain stakeholders in the Dharavi area. Fourth, student volunteers from the Tata Institute of Social Sciences, assisted us in the numerous field interviews that were conducted. These four organizations improved the quality of our work and our creative capacity. Thus, the scale of urban India's waste management problem, our own familiarity with the Indian context, and our strong network in the country, led us to focus the geographic scope of this paper on the city of Mumbai, India.

Informal Recycling in Urban India - An Overview

The Indian informal waste management & recycling sector involves six distinct groups of players. First, the process starts with the waste generators; this includes households, offices, large retail spaces, and any other buildings that tend to accumulate 'dry' waste. For the purpose of this thesis, dry waste is defined as any kind of refuse that is not 'wet' food waste or bio-hazardous material. Typically, a basket of mixed dry waste contains paper, plastic, metal, and glass. Waste management companies contracted by the city municipality collect any kind of waste produced by these waste generators and takes it to landfills where it is either dumped without further treatment or incinerated. More recently, waste-to-energy machines have been introduced to clear some space within landfills. However this niche segment of the industry is in a nascent stage in Mumbai and does not yet play a significant role in the management of urban Indian waste. The second group of players are the waste pickers (kachrawalas). For the most part, they tend to be categorized of women looking for part-time employment to supplement their household income, homeless or transient adult men in between jobs, or young school age boys looking to alleviate their families' economic desperation. These waste pickers walk through the landfills and collect waste that they know to be of recyclable quality. Kachrawalas are famed for their ability to expertly pick high grade waste from tons of mixed waste. They then sell their collection to the third group of players, small scrap dealers buyers (*kabadiwalas*). In some cases, these waste buyers also source their supply directly from waste generators by going to households door-to-door. At the kabadiwalas' small street-side shops, the waste goes through a preliminary sorting process where waste is separated into piles based on type (plastic, metal, cardboard, e-waste). The fourth group of players, industry processors, buy waste wholesale from the small scrap dealers. At this step of the process, the waste goes through both more rigorous sorting, categorized by a multitude of differentiators such as quality and color, as well as machine processing such as the crushing of plastics or baling of cardboard. The processed waste is then sold to recyclers, who convert the processed waste back into raw materials suitable for production of new products. Finally, in the last step, the recycled material is sold to manufacturers (the likes of Coca Cola and Unilever) who create finished products. The following image provides a rudimentary version of this supply chain, although in reality there are more middlemen who occupy intermediary positions.

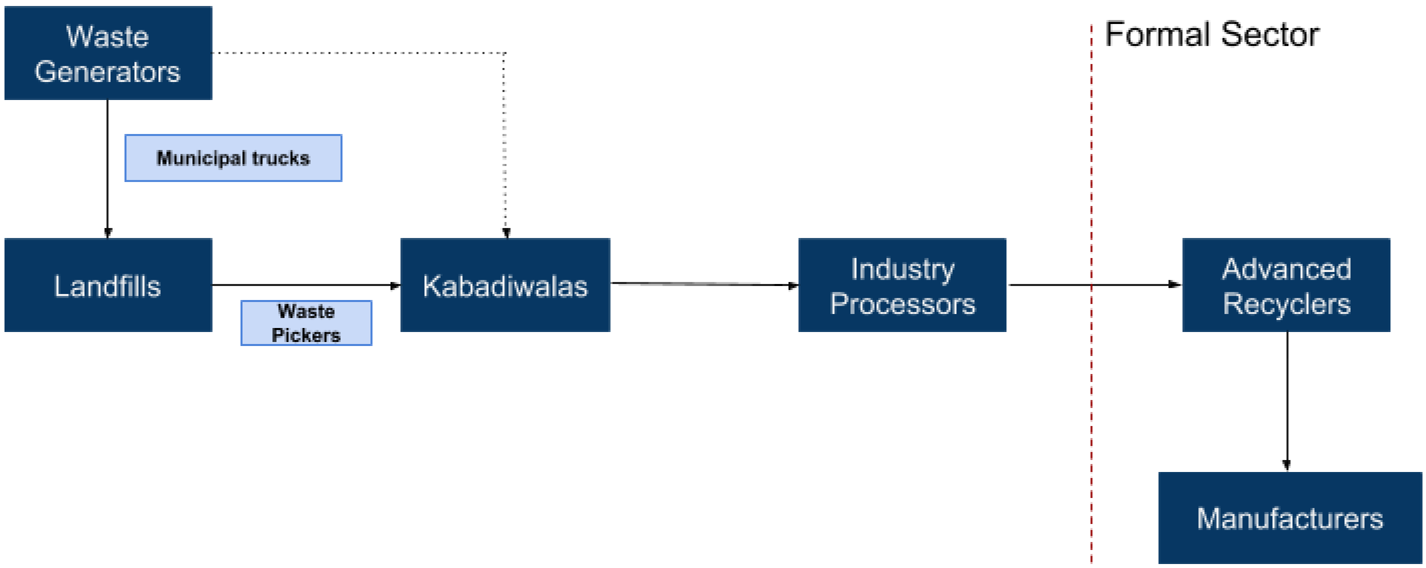


Image 1.0 - Overview of the Waste Recycling Supply Chain in Mumbai, India

In this process, until reaching the actual recycling phase, the sector is largely informal and unconsolidated. Informal workers at the bottom of the value chain (waste pickers and scrap dealers such as the smaller kabadiwalas) live in poverty, reside in slums, and earn $3-$9 a day from the recyclable plastics that make the red solo cups, cutleries, and water bottles we use every day. There are four key problems preventing these workers from lifting themselves out of poverty.

First is a lack of horizontal connectivity with their peers: one picker with another or one scrap dealer with another. As a result, these workers are only able to deliver to their respective procurers (dealers for pickers, processors for dealers) in low quantities, resulting in suboptimal per unit pricing and are unable to benefit from the advantages of economies of scale. Second, there is also a lack of vertical integration between the different players leading to scarcities in supply or a lack of demand because the market participants are not well connected with each other. A kabadiwala, for instance, is normally acquainted with just one industry processor. This severely limits their bargaining power and their ability to scale their businesses. Third, a lack of easy access to capital puts practical limits on the amount of waste the intermediaries are able to process. The culture of waste management in India is such that waste generators, especially individual households, expect payment from kabadiwalas for recyclable quality trash such as newspapers or plastic containers. Kabadiwalas pay a certain amount to these households to procure the waste, sort it in their stores, and then sell it to industry processors for a margin. Thus, if kabadiwalas do not have enough working capital to first pay the households for their waste, they are not able to increase the quantity of waste they process even if they are unconstrained on all other fronts. Finally, fourth is a combination of societal reasons that result in the discrimination and marginalization of waste workers. There is an implicit manifestation of the caste system in the sector wherein its members are, predominantly part of the 'lower' castes. Additionally, low average educational attainment also reduces the upward mobility of future generations.

Hypothesis and Research Focus

Solving any single one of these problems is insufficient for the holistic empowerment of the sector since adverse effects of the remaining issues will continue to create problems for the stakeholders. Since each of these players suffer from slightly different problems, we realized that it was more beneficial to focus our attention on one section of the supply chain with positive externalities for the remaining stakeholders. Waste pickers occupy the bottom of the pyramid and are the most impoverished members of this supply chain. However, given an acute lack of structure to their daily activities, it is highly infeasible to create an optimized logistics solution to improve their livelihood. Thus we turn to the next stakeholder - the kabadiwala.

We propose the creation of a tech-enabled marketplace that connects and consolidates the informal section of the industry with the kabadiwala at its center. The model attempts to ameliorate the core constraints that kabadiwalas face by increasing their volume of waste supply on the input side, and their unit margins on the output demand side.

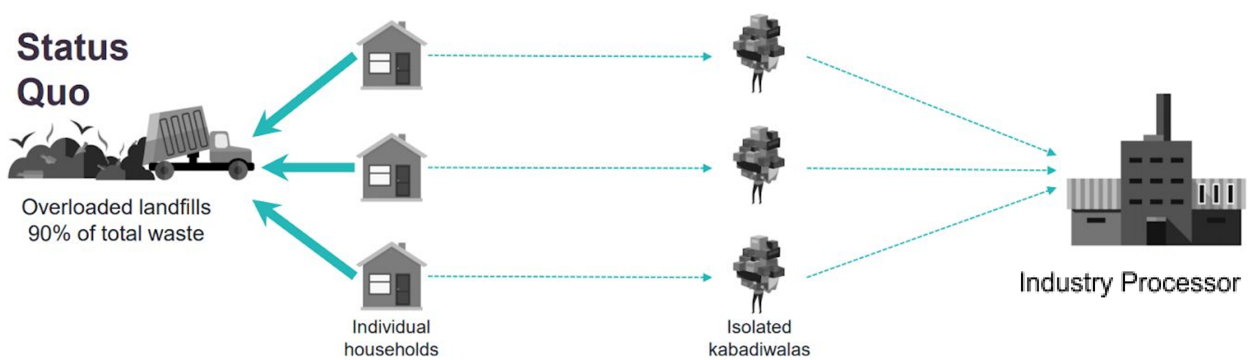


Image 2.0 - Existing Supply Chain of Waste with a Focus on the Kabadiwala

As image 2.0 depicts, Kabadiwalas today receive low volumes of waste from waste generators since they do not a) have the necessary connections to approach large generators, b) lack the working capital to service large generators, and c) are socially stigmatized for their social class and profession. On the output side, since they are only acquainted with limited number of buyers, they do not have bargaining power to increase their revenues.

Image 3.0 demonstrates the reimagined marketplace model that addresses all of these specific constraints that limit the potential of kabadiwalas. On the input side, by connecting kabadiwalas with bulk waste generators such as housing complexes and schools, we are able to increase their daily volumes. On the output side, by pooling waste across multiple kabadiwalas and delivering in bulk to recyclers, there is an increase in unit margins.

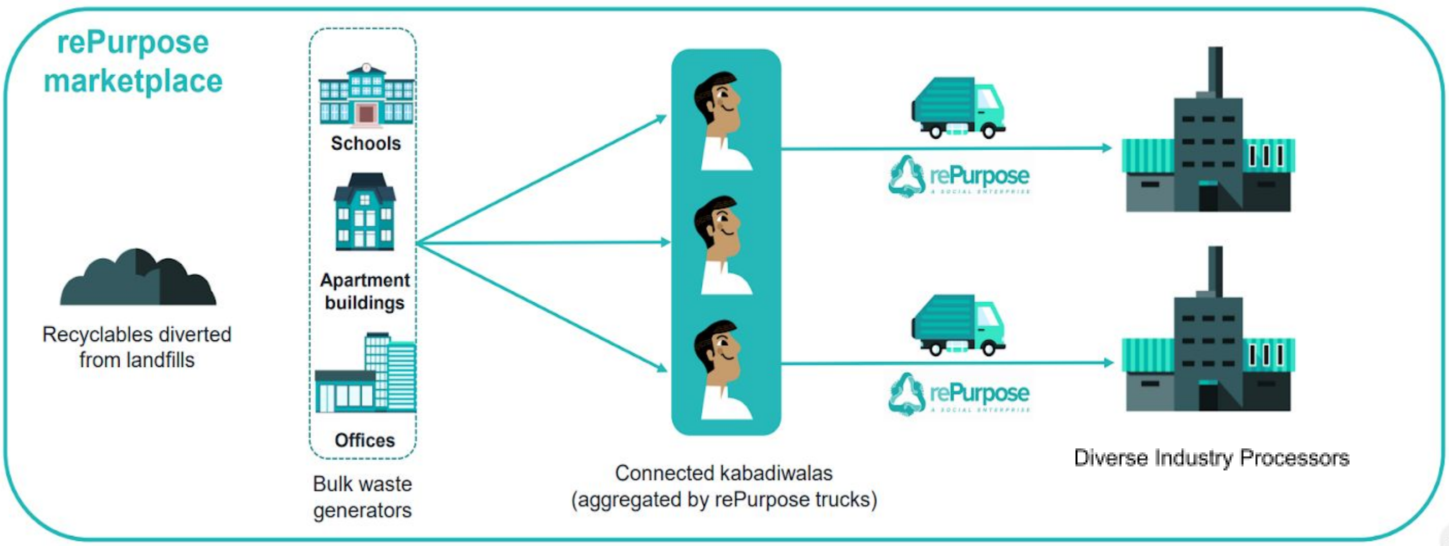


Image 3.0 - Proposed Marketplace to Increase the Profits of Kabadiwalas

The following six hypotheses will be tested from the creation and implementation of this tech-enabled marketplace.

1) Bulk waste generators are willing to sell their waste to kabadiwalas instead of sending it to landfills via the municipal trucks. This is a more qualitative behavioral change that we are attempting to forecast for through interviews with relevant housekeeping staff.

2) Kabadiwalas have the capacity, and the willingness, to service bulk waste generators in addition to their usual door-to-door household calls.
3) Kabadiwalas are able to use a tech-enabled platform to conduct business.
4) Aggregating across multiple kabadiwalas and delivering in bulk to industry processors does result in higher margin, given the implicit benefits of economies of scale that will be incurred.
5) The model is able to allocate waste in an efficient manner, even given other exogenous factors, and ultimately reduces the waste being added to Mumbai's landfills, benefitting both the recycling industry and the city's environment.
6) The marketplace is able to recover costs and is therefore financially sustainable on the long-run without any additional funding or intervention from external sources.

The methodology section of this paper provides more details on the proposed model, the creation of the marketplace, as well as how we plan to test the hypotheses with on-the-ground activities.

RESEARCH SIGNIFICANCE AND AUDIENCE

There are two distinct learnings produced by this paper. On the qualitative side, the paper contains a wealth of knowledge on the operations and workings of the informal recycling industry in India amassed through interviews with various stakeholders, industry experts, and academics. On a more quantitative note, the paper also includes a model that replicates the workings of the proposed marketplace as well as data collected from 48 simulations of said marketplace under different scenarios.

Significance of Qualitative Research on the Informal Recycling Industry

Given the interdisciplinary nature of urban waste management, we believe that four audience groups would be interested our research. First, *municipal policymakers* are interested because the solution, if implemented at scale, can save municipal budget dollars by boosting informal collection as well as reducing the size of landfills within city limits. Second, *institutional players in international development* (nonprofits, foundations, think tanks etc.) are interested because this innovation can potentially be replicated in other regions of the world, bringing about catalytic impact. Third, *impact investors and venture capitalists* are interested because if scaled and commercialized, the project can be spun into a social enterprise initiative that could present itself as an investment opportunity. Fourth, *academic researchers* in operations, urban development, and environmental studies could potentially look to our research as a basis for further research within this space.

Significance of the Marketplace Model and Simulated Data Results

The co-authors of this thesis were successful in winning the 2018 President's Engagement Prize awarded at the University of Pennsylvania. The prize, awarded competitively on a yearly basis, provides $100,000 in funding for graduating seniors looking to undertake socially impactful projects worldwide in the following year. We received this award for our prospective work in implementing our proposed waste recycling marketplace model in Mumbai, India commencing July 2018.

Thus a scaled version of the model that was built as part of this thesis to replicate a marketplace will be used on a day-to-day basis while we begin operations in India in the subsequent months. The constraints of the model, the data points that were varied in the 48 simulations, the structure of the decision variables, and the final objective are all based on realities in Mumbai that we were able to learn from our research. Thus, the model is perfectly aligned with our operational needs and will be used, at least for the first few months until a more sophisticated larger scale back-end platform is built, to efficiently allocate waste between the marketplace's input side stakeholders (waste generators and kabadiwalas).

In addition to this practical implementational usage, the model is also successful in validating some of the core assumptions and hypotheses that were previously mentioned. The 'Phase 3' section of this paper provides further details of the learnings from summary statistics that were generated from our simulations of the model.

LITERATURE REVIEW

In 2014, the World Bank estimated that up to 2% of urban populations in low and middle income countries are part of the informal waste sector – this means that more than 15 million people scavenge, sort, and process recyclable materials such as plastic, metal, and paper around the world today (Nandy et al. 2015). Without informal workers involved in every step of the recycling value chain, city governments, with their limited capacities and budgets, would be unable to handle thousands of tons of waste generated by households and industries on a daily basis, potentially rendering cities worldwide to whole dumping grounds.

The informal solid waste recycling industry is especially vibrant in Indian cities. A 2015 country-wide study estimated that waste pickers ("rag pickers") and informal dealers ("kabadiwallas") in India scavenge and process anywhere between 9,800 and 19,000 tonnes of recyclable plastics every day (Nandy et al. 2015). This sector thus provides immense societal benefit in three distinct ways. First, it generates savings for municipal governments: in New Delhi, 12–15% of solid waste is collected by the informal sector, saving the city an estimated 4 – 5 million USD per year (Aleluia & Ferrão 2016). Second, the work of these informal workers produce an obvious environmental benefit – one calculation suggests that informal waste recycling in Delhi reduced CO2 emissions by almost 1 million tons annually, far exceeding reductions of government-run recycling plants in the formal sector (Chintan 2009). Finally, solid waste recycling provides economic opportunities for the vast urban poor: at least 100,000 rag pickers operate in Delhi alone, and urban India is home to anywhere between 900,000 – 1.6 million kabadiwallas (Nandy et al. 2015).

A considerable collection of case studies in waste-related academic journals has extensively documented the solid waste management systems of Indian cities over the years, specifically detailing the roles of players involved in informal systems (Yedla & Kansal 2003, Agarwal 2005, Zia & Devadas & Shukla 2008, Baishya & Mahanta 2013, Suthar & Rayal & Ahada 2016). Despite the tremendous societal benefit of informal waste recycling, the supply chain is extremely unfair to workers at the pyramid's bottom. Rag pickers capture around 15% of the materials' final market value and make on average 150-300 rupees ($2.3-$4.5) per day (expert interviews, Mumbai 2017). Many of these pickers have traditionally been part of the "untouchables" caste (dalit); cultural perceptions associated with the legacy caste system coupled with illiteracy due to a lack of any education prevent these pickers from breaking the generational barrier to pursue more high-paying and dignifying jobs. Many pickers migrated from rural areas in other parts of India (75% in a survey conducted in Bangalore (CHF International 2010)), and the vast majority are either homeless or live in slums throughout the cities. Furthermore, the filthy work environment presents severe health hazards for rag pickers: a survey conducted in Chandigarh found that waste workers were plagued by various respiratory disorders, injuries and allergies with prevalence rates of 12.3%– 17.6%, 4.9%–44.4% and 35.3%–48.9% respectively (Ravindra & Kaur & Mor 2016).

Although the suffering of rag pickers is commonly known in India, existing scholarly research into these socio economic problems is rather limited, especially compared to the vast volume of descriptive case studies on solid waste management systems in Indian cities that document the economic role played by pickers and the broader informal recycling supply chain. Most literature on the topic comprises of small-scale demographic surveys and contain little analysis that could yield actionable insights on opportunities to generate income for this marginalized population. Moreover, even less research is directed towards informal workers who work under dealers and wholesalers: they earn admittedly more and more stable incomes than pickers ($5-6 a day), but still work in hazardous environments, live in urban slums, and remain in abject poverty. Nonetheless, despite the overall limitations of literature, scholarly interest in both health hazards of waste picking and child labor within recycling has sustained over time, producing numerous descriptive studies of lives of child pickers as well as pickers' health outcomes in major cities like Pune, Mumbai, and Bangalore (Hunt 1996, Dalal & Rahman & Jansson 2008, Chatterjee 2015).

Given this grim status quo, how could we innovate and push more value downstream to empower informal workers in the Indian recycling industry? A diverse group of international development institutions have published reports and given recommendations on this issue over the last two decades, notably GIZ (German development agency), WIEGO (Women in Informal Employment: Globalizing and Organizing), Chintan Environmental Research and Action Group, and more recently, MIT D-Lab. Historically, empowerment initiatives in this space can be roughly divided into two categories: 1) public-private partnerships 2) cooperatives and micro-enterprises.

First, a number of public-private partnerships (PPPs) have emerged over time in a handful of cities globally in the hopes of integrating these informal workers into the formal municipal solid waste management system. Pune, a city of 3.1 million people in the Indian state of Maharashtra, has received an especially significant level of attention from academia. Waste pickers there were initially unionized in 1993 ("KKPKP"), ensuring that they receive legal recognition as sanitation workers and contributors to the city's solid waste management. In 2008, the KKPKP launched a PPP with the Pune Municipal Corporation (PMC) named SWaCH, an initiative that sees pickers conduct door-todoor collection of waste from households (Bhaskar & Chikarmane 2012). This PPP now comprises of at least 2,500 uniformed members with ID cards, delivering collection services to more than 350,000 households in the city. PPPs like SWaCH ensure legal recognition, pickers' access to waste, and long-term sustainability of these livelihoods. However, their success largely depends on the political will of municipal governments as well as existing structures of collective action by waste pickers to initiate the conversation, both factors that ecosystems in most other Indian cities lack.

Secondly, efforts to organize waste pickers into cooperatives and micro-enterprises have proven fruitful in many Latin American countries and a few Indian cities as well. The prime example of this is Stree Mukti Sanghatana (SMS), a Mumbai-based cooperative where 600 women waste pickers deliver dry waste collection services to clients ranging from institutional campuses to residential apartments. In addition, SMS developed a decentralized micro-entrepreneurial model where pickers convert organic waste to methane and fertilizer on-site using biogas plants and composting stations, selling the products back to households and local businesses in exchange for cash (GAIA 2012). Initiatives like SMS have functioned well in local contexts, but they could often take decades to mature, and more importantly, these local organizations lack the capital to increase penetration to the vast majority of pickers who are currently unorganized.

As a result of the challenges faced by PPPs and waste picker cooperatives, recent innovations in the informal recycling space have turned their attention to three new business models: external producer responsibility (EPR), direct engagement with households, and social entrepreneurship. First, EPR is a concept increasingly embraced by manufacturers of paper- and plastic-based products that both generate large amounts of waste as well as use a significant portion of recyclable waste in the production process. These companies are re-envisioning processes such as material sourcing, product design, distribution, and reclamation to make their operations overall more circular and sustainable (MIT D-Lab 2016). Innovators in the informal recycling space have begun to take advantage of this attitude shift: waste-picker cooperatives in Brazil were able to engage with Danone, a French food multinational corporation, and helped them achieve their EPR goals by supplying recycled packaging. The program not only achieved a 40% recycling rate of product packaging for Danone, but also increased monthly picker incomes by 50% (MIT D-Lab 2016).

In addition to engaging manufacturers who are end beneficiaries of the informal recycling supply chain, innovators (Pom Pom in Delhi, Daily Dump in Bangalore) are also looking towards the very source of this waste: households. If households themselves segregated by dry and wet waste, pickers need not to extensively sort through the garbage, using the saved time to collect more waste and earn more money. In addition, as cities modernize and governments aim to shut down open landfills within city limits, pickers' access to waste is being increasingly threatened, highlighting the need to engage households directly to ensure waste pickers' long-term livelihoods.

Ultimately, social enterprises that use business principles, private sector capital, and profit making to catalyze, scale, and sustain social impact are becoming increasingly prominent in the informal recycling space. Sampurn(e)arth, a Mumbai-based social venture, has constructed two recycling centers with sorting and crushing capacity, generating profit from the sale of processed materials while paying waste pickers fair wages. These business models bypass the funding challenge faced by community groups and nonprofits with little revenue-making ability.

Despite these recent innovative business models and modes of stakeholder engagement, a lack of recent discourse in the international development space, up-to-date data sources on the economics of the recycling supply chain, and actionable qualitative research into the lives of waste workers persist in India's informal solid waste recycling industry. This project aims to learn from failures associated with legacy initiatives, advancements in technology, and changing stakeholder attitudes (households & manufacturers) to implement a pilot social entrepreneurial platform that aligns economic interests of value chain players, make linkages between supply chain steps overall more efficient, and ultimately generate more income for informal workers in this industry in urban India.

METHODOLOGY OVERVIEW

Research for this paper can be divided into three distinct phases. Given the relative lack of tangible qualitative and quantitative data in existing literature that could be used for the ideation and creation of our optimization platform, the first two phases were largely composed of in-person interviews and industry practice observations in India. The information gathered through these field visits then became the foundation upon which the third phase was designed. Phase 1 involved informal interviews with industry experts, academics, Penn professors knowledgeable about our research area as well as with private sector participants in the formal waste management sector. Phase 2 involved the co-authors of this paper travelling to Mumbai, India to observe everyday operations in the informal space as well as to conduct extensive interviews with direct stakeholders to validate some of the underlying assumptions of the proposed marketplace model. We received IRB documentation to conduct these interviews in Mumbai.

Phase 3 utilizes the depth of knowledge from the previous two phases to create a base model of the input side of the marketplace. The goal of the model is to use real waste production data, as well as real constraints on the capabilities and willingness of the waste generators and kabadiwalas, to best allocate individual kabadiwalas to pick up waste form individual waste generators. The model created is dynamic and able to produce different optimal solutions based on two factors that were varied, i) the amount of traffic which affected the maximum distance kabadiwalas were able to travel and ii) the quantity of waste generated by each kabadiwala. We simulated the model for 48 different combinations of these two uncertain variables to capture the average allocation of waste as well as multiple other useful learnings.

PHASES 1 & 2 - METHODOLOGY AND FINDINGS

Phases 1 and 2 - Methodology

During the first two phases, we conducted two trips to Mumbai. Once in November 2017 and once in January 2018, in order to conduct in-person interviews with waste pickers, housekeeping staff at waste generation sites, kabadiwalas (scrap dealers), waste truckers, and industry processors. The goal of the two field trips was to better understand the challenges, bottlenecks, and incentives of the diverse stakeholders as well as to gauge their attitudes towards the usefulness of such an agglomeration platform and their willingness to be a participant of the marketplace. To this end, the interviews were approached in a semi-structured manner: qualitative questions were posed in an open-ended format whereas quantitative questions were posed directly as they were aimed at obtaining specific data points to establish a baseline for the eventual comparison with simulation results (e.g. monthly turnover, income, current cost of transportation). Interviews were conducted orally in collaboration with local volunteers who spoke Hindi and Marathi. In addition, we reconnected with existing implementing partners and new collaborators to obtain a comprehensive landscape of the informal recycling supply chain in the city of Mumbai – this allowed us to put in-person user interview results into context and assess overall fit of the service with the industry today and in the near future. Finally, being present at landfill sites, visiting the stores of kabadiwalas, and touring the facilities of waste generators provided us with invaluable understandings of the realities on-the-ground more useful than any individual interview.

Phases 1 and 2 - Discussion of Findings

This section summarizes our learnings in Mumbai's recycling industry, categorized by the different players that are significant stakeholders in the sector.

Bombay Municipal Corporation (BMC) Operations

1. The Brihanmumbai Municipal Corporation (BMC) is the civil body governing infrastructure issues in Mumbai. They have recently instituted a new law that requires bulk waste generators such as housing societies and corporate buildings to segregate their waste into dry and wet waste from the second of January, 2018. This is an excellent opportunity to enter a thus far untapped source of waste. Since these generators did not historically segregate their wet waste from dry, the majority of the waste was invariably sent to landfills. However, this forced segregation could enable direct transportation to *kabadiwalas* who could potentially sort through a basket of dry household waste for recyclable materials.
2. The city of Mumbai produces around 9500 tons of waste on a daily basis. Of this total amount of waste generated, 7500 tons are dumped in landfills. The remaining 2000 tons is either recycled by the informal industry, incinerated through various waste-to-energy

efforts, littered in surrounding barren areas or water bodies, or remains uncollected inside city limits.

3. Mumbai is divided into twenty four 'wards' with their own separate administrative units. These units hire private contractors to collect waste from public dumpsters using small trucks that have a capacity of 1.5-3 tons. On average, contractors receive $11/kg of waste transported. The waste is then consolidated at central collection centers called transfer grounds, of which there are about 5 or 6 spread across the city, from where it is then transported to landfills via compression vehicles that average a 6.5 ton capacity. The government pays $9/kg for this disposal service. Solid Waste Management accounts for around eight percent of the total municipal budget for the city of Mumbai.
4. There are three dumping grounds that service the Greater Mumbai area - Kanjur, Mulund, and Deonar. Allocation to each dumping ground depends on the geographic proximity to the collection center and the daily allotted capacity of the landfill. Deonar is an 'open dumping ground'; there is limited to none scientific process in how the waste is dumped here. In contrast, Kanjur, which is newer, is handled more effectively and uses relatively novel engineering to increase the longevity of the space and reduce its environmental impact.
5. The introduction of the Goods and Services Tax (GST) in India have directly adversely impacted the profit margins of recyclers and some of the larger processors operating in the formal section of the economy. In addition, the reduction in profit margins higher up the supply chain have resulted in indirect reductions to profits lower down the chain,

impacting even the informal section. Large recyclers and processors in the formal section of the supply chain pay between five to eighteen percent in taxes.

Waste Pickers - Kachrawalas

1. Waste pickers form perhaps the most marginalized sections of Indian society with a majority of them resorting to waste picking out of necessity and a lack of other career options. Common among the demographic composition are women looking to supplement their household incomes, homeless men looking for a day-by-day source of revenue, and young school-age boys from surrounding low-income areas. This profession is especially damaging for the latter group as it restricts their future potential and pushes them into a cycle of poverty. On average, waste pickers earn 100-200 rupees a day ($550-$1000 annually). While they do not have any set storage space, they tend to accumulate waste over the course of a few days and sell about twice a week to kabadiwalas.
2. Given their lack of education on safety standards and access to supplemental income that would allow them to buy accessories such as gloves or masks, the majority of the waste pickers operate in substandard conditions exposing themselves to a variety of health concerns in the process.
3. Waste pickers typically operate around landfills in specific regions and do not have a mode of transportation to provide them with access to *kabadiwalas* in any other region. Given this restriction, waste pickers form strong relationships with the one or two

vendors that they supply to on a regular basis. Cash advances are often extended to them by the *kabadiwalas* on a trust-basis.

Scrap Dealers - Kabadiwalas

The information contained below about the daily operations of kabadiwalas are based on interviews conducted with over 30 scrap dealers across different regions of Mumbai. Individual metrics may vary based on the size of each scrap dealer and their geographic location. The data presented is thus an average of the findings. Where applicable, we provide a range that encompasses the differences between Kabadiwalas.

1. Kabadiwalas receive their daily supply of waste through three sources: I) household visits, ii) delivery from waste pickers and iii) direct drop-offs by people living in the surrounding area. Waste pickers tend to operate predominantly in areas close to landfills and are therefore not a significant source of supply for the average kabadiwala in the city. Drop-offs from surrounding inhabitants are also not extremely common given that only a relatively small percentage of the population is savvy enough to recognize waste that holds recyclable value, and more importantly, believes that the effort to collect the waste and deliver it to the kabadiwala is worth the money. Thus the house calls made by kabadiwalas tend to be the most significant source of waste supply.
2. For kabadiwalas who do depend on supplies of waste from waste pickers, two problems prevail. First, in areas where waste picker activity is low, there are long periods of time when the *kabadiwalas* are forced to operate below capacity, with some of the

interviewees noting their frustration with the lack of available waste and their consequent disillusionment in the long-term feasibility of their business. Second, in areas where waste picker activity is high, *kabadiwalas* are constrained by the lack of physical space to store excess waste as well as working capital and have to sell the waste off on a daily basis in order to 1) clear the limited space for processing for the next day 2) gather enough cash to operate the business the following day.

3. In general, kabadiwalas own vehicles to transport waste from households to their scrap shops. These vehicles can range from bicycles that hold no more than 10 kgs of waste to larger rickshaws that can accommodate up to 50 kgs. The average kabadiwala has a modified scooter than can take about 20 kgs of waste.
4. The transportation of waste from the *kabadiwalas* to the industry processors differs by region and scale. However, there are three predominant categories of transport. First, in the majority of cases, industry processors own their own trucks that they send out to circle through the regions more heavily populated by *kabadiwalas* looking to source enough waste to meet their demands for the day. *Kabadiwalas* sell directly to these truck drivers and are paid in cash on the spot; in a lot of the cases, they are unaware of the real owners behind the truck drivers. Second, there are independent third party trucking agencies that can be hired to transport waste by either stakeholder depending on their subjective needs. Finally, in a minority of the cases, large scale *kabadiwalas* own their own trucks that they used to send aggregated waste in bulk to a few processors with whom they have established and trust-based relationships. In all instances, rates are negotiated on the spot by the two transactors and hard cash is used to settle the trade.

5. Kabadiwalas require at least 5 kgs of waste to consider doing a household visit to make it worth their time. This number of course is a rule of thumb and is dependent on circumstantial conditions such as the physical distance to the household, the availability of laborers to pick up the waste, the supply of waste so far in the day, and the quality of waste being picked up. For instance, 3 kgs of steel, which has high margins, from a household 200m away would be favored over 8 kgs of plastic from a household 1 km away.
6. About 10 percent of the waste processed by kabadiwalas can be conservatively assumed to be of bad quality given rampant systemic cheating. These scrap dealers, as part of candid conversations, were willing to admit that they mixed poor quality waste along with their normal load when selling upstream to recyclers or industry processors. There was no moral guilt associated with such action, hence perhaps their transparent admissions of it, because it was seen as simple standard industry practice that the buyers also expect the cheating and price it in accordingly. For instance, an industry processor would pay the rate of 9 kgs of waste to a 10 kg transaction because he expected to be swindled given the culture of the industry. Therefore by *not* cheating, the kabadiwala would lose money.

Waste Generators (Households)

1. The average person in a large Indian city such as Mumbai generates about 0.5 kgs of waste everyday. The average household size is five, bringing the total waste produced to around 2.5 kgs.

2. Household waste is predominantly made up of wet waste that can be composted but is not useful for recyclers. A standard 5 member household produces about 0.75 to 1 kilo of waste in a day. Of this dry waste portion, plastic makes up about 30 percent, paper products about 40 percent, and metal about 5 percent. The majority of recyclable waste is composed of packaging materials.
3. Industry experts believe that if the municipality is strict about enforcing the afore-mentioned source segregation law, it would take from five to ten years for the majority of housing societies to create the necessary infrastructure to accommodate the requirement.

Industry Processors

1. Industry processors tend to be concentrated within several specific areas of the city of Mumbai (Dharavi slum, Mondala) and can also be found in various sizes fulfilling different amounts of the processing functions that precede the recycling stage.
2. While *kabadiwalas* often deal with more than just one type of waste - capable of sorting through a basket of dry waste to separate categories of recyclable materials such as plastics, glass, and metal - the industry processors tend to specialize within one category or subcategory of material. This is because their operations require the usage of specialized machinery and equipment that often only caters to a certain type of waste.
3. Industry processors also have occasions where they are forced to operate below capacity due to a lack of adequately matched supply. In addition, productivity of plastic processors

drops by approximately 70% during monsoon season as they are unable to dry the plastics at an adequate speed.

Pricing Variations and Average Rates

Prices are extremely deviant even within a single day depending on the size of the stakeholder, their location in relation to the player higher up the supply chain, seasonal demand changes, intra and inter day traffic movements, changes in oil prices and other raw materials which influence demand from manufacturers (for instance, virgin plastic becomes cheaper when oil prices fall, thus reducing demand for recycled plastic), and systematic supply shocks such as public holidays or festivals. The following numbers are purely averages and in no way are representative of individual stakeholder rates.

Plastic PET bottles (per kilo rates)

1. Households receive various prices ranging from 7 to 11 rupees.
2. Waste pickers receive between 12 to 14 rupees from kabadiwalas.
3. Kabadiwalas are able to sell sorted hard plastic (such as the body of a PET bottle) for around 15 to 16 rupees.
4. Higher up the value chain the margins also increase. Industry processors receive around 30 rupees and recyclers receive 65 to 70 rupees.
5. Rates of hard plastic vary between 1 to 3 rupees on a daily basis and as much as between 30 to 40 percent annually.

Paper (per kilo rates)

1. Households receive various prices starting at around 6 rupees for newspapers and around 11 rupees for cardboard.
2. Kabadiwalas are able to sell newspapers, textbook papers, and similar qualities of paper for about 12 to 13 rupees.
3. Paper mills, identical to large industry processors or recyclers, receive 40 to 50 rupees from the manufacturer.

Other Recent Innovation in the Industry

As noted in the Literature Review section of the paper, there exist around 10 to 15 players across the country who are attempting to improve the efficiency of this sector. The majority of these players are involved in the creation of 'Material Recovery Facilities' (MRFs) that essentially consolidate the market with an end to end solution that eliminate the intermediary players. MRFs capture the collection, segregation, and processing of waste in one in-house establishment and sell directly to the recyclers. This method in theory has the potential to capture large margins, given the lack of any middlemen, and circumvents the obstacles of trying to untangle the complicated stakeholder networks in the existing industry. However, in practice, these facilities tend to be extremely capital intensive and difficult to scale. The fixed costs associated with real estate and machinery purchase, labor costs, and legal obligations deter easy expansion. Moreover, such facilities also face backlash from the intermediaries that they shut out of the value chain which can prove significantly damaging to their operations.

PHASE 3 - METHODOLOGY AND FINDINGS

Phases 3 - Input Model Methodology

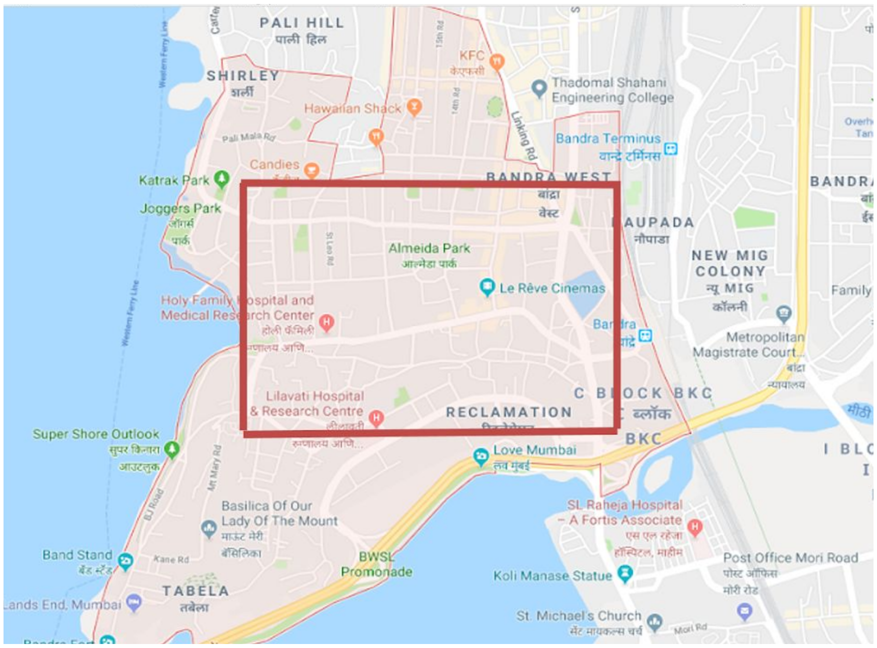
As part of this phase, we created an optimization model using the standard linear programming engine of *Advanced Solver.* The goal of the model was to optimally allocate the waste generated by 4 bulk waste generators to 12 kabadiwalas in their locality.

Establishing the Stakeholders

We chose to work with 4 bulk waste generators and 12 kabadiwalas as this was the scale at which we hoped to commence on-the-ground operations in Mumbai in July 2018. Given that this model is expected to be used on a daily basis, it was imperative that its specifications meet our requirements for the pilot period of the marketplace. The 12 kabadiwalas are symbolized by the letter 'K' followed by a numerical indicator (K1 through K12). Similarly the 4 waste generators are denoted by the letter 'G' followed by a numerical indicator (G1 through G4).

However, given that we do not have the exact locations of the stakeholders we would be working with, we decided to randomly distribute the kabadiwalas and generators within the center of the *Bandra* area of Mumbai where we hope to start implementation. Image 4.0 depicts the limits (solid lines) of the *Bandra* area (highlighted in red) which were used to create the upper and lower bounds for the random distribution, structured as a grid. From West to East, the area spans around 5 kms (5000 ms). Accordingly, the lower bound of the X-Axis for the random distribution was set to 0 and the upper bound was set to 5000. From South to North, the limits of *Bandra* considered on average spans around 3.5 kms (3500 ms). Thus, the lower bound of the

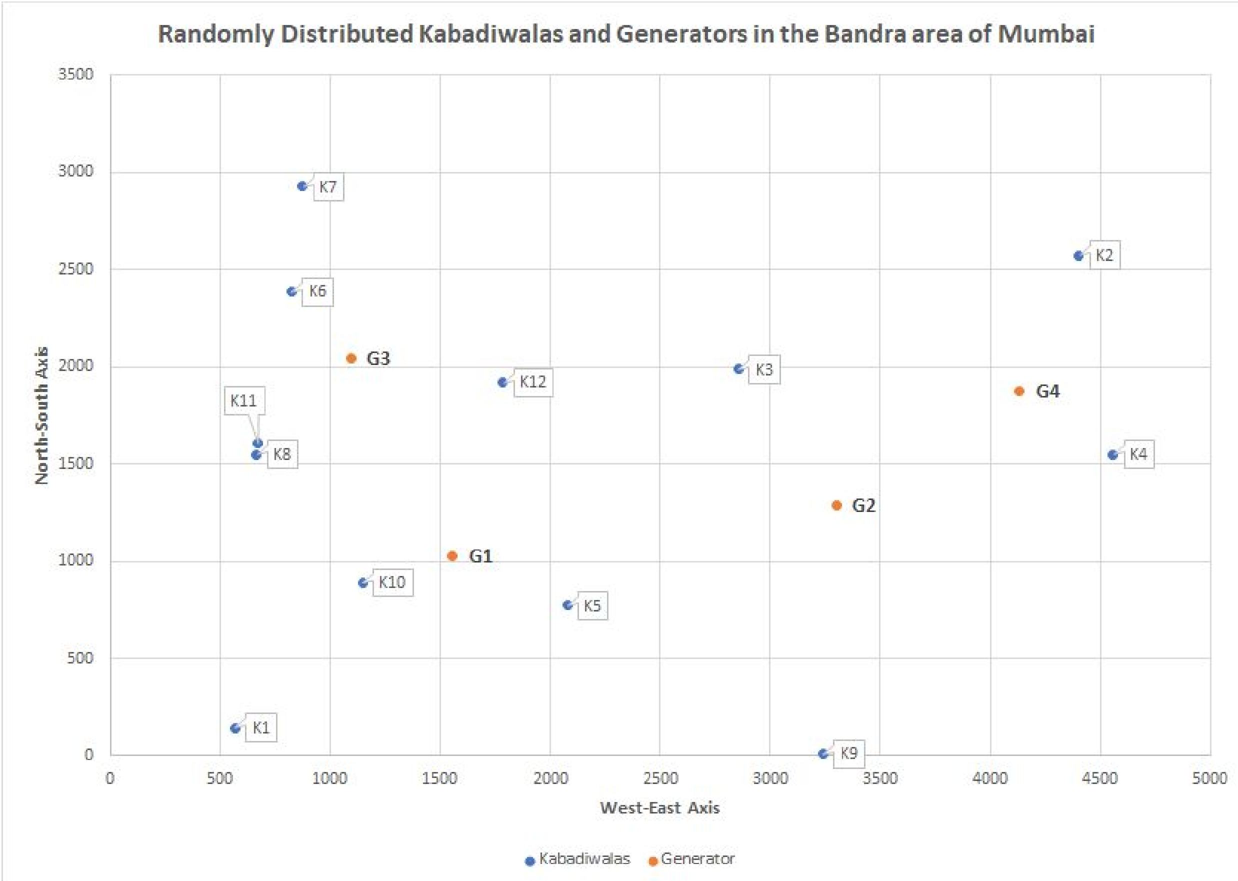
Y-Axis was set to 0 and the upper bound was set to 3500. Once we had these limits, the Kabadiwalas and Generators were assigned randomly distributed X and Y coordinates such that they were randomly dispersed throughout the area. Table 1.0 depicts these coordinates and Graph 1.0 visualizes their distribution.



<u>Image 4.0 - Limits of Bandra Incorporated into the Grid</u>

Random Distribution of Kabadiwalas and Generators in the Bandra Area						
	Y-Axis	X-Axis			Y-Axis	X-Axis
K1	142	568		**G1**	1024	1552
K2	2574	4404		**G2**	1287	3298
K3	1987	2856		**G3**	2041	1091
K4	1548	4558		**G4**	1876	4133
K5	772	2077				
K6	2385	823				
K7	2927	874				
K8	1549	665				
K9	10	3241				
K10	889	1145				
K11	1605	668				
K12	1919	1786				

<u>Table 1.0 - Random Assignment of X and Y Coordinates to the Stakeholders</u>



Graph 1.0 - Stakeholders Randomly Assigned to a Subsection of Bandra

Creating the Decision Variables

The first set of decision variables were straightforward to create as they simply involved a matrix of 12 kabadiwalas against the 4 generators. Each individual cell holds the volume of waste (in kilos) collected by the corresponding kabadiwala from the corresponding generator. For example, cell B3 records the waste collected by kabadiwala K1 from generator G1. This set of decision variables are also divided into two separate matrices thus allowing each kabadiwala to take up to 8 total trips. This structure also allows each kabadiwala to visit any one generator up to two times.

In the remainder of the paper, the subscript ‘i’ will be used to indicate which kabadiwala is being considered and the subscript ‘j’ will indicate which generator is being served. Each of the individual cells in the first matrix (trips one to four) will be denoted as KG_{ij}. For instance, the output in B3 will be denoted as KG_{11}. Each of the individual cells in the second matrix (trips five to eight) will be denoted in lower case as kg_{ij}. For instance, the output in I3 will be denoted as kg_{11}. Image 5.0 shows a snapshot of the model incorporating the first set of decision variables.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Decision Variables - Waste Collected by Each Kabadiwala from Each Generator												
2	**Trips 1-4**	**G1**	**G2**	**G3**	**G4**			**Trips 5-8**	**G1**	**G2**	**G3**	**G4**	
3	**K1**	0	0	0	0	0		**K1**	32.5	32.5	0	0	65
4	**K2**	0	32.5	0	32.5	65		**K2**	0	32.5	0	32.5	65
5	**K3**	0	32.5	0	32.5	65		**K3**	0	32.5	0	32.5	65
6	**K4**	0	0	0	32.5	32.5		**K4**	0	0	32.5	32.5	65
7	**K5**	32.5	0	0	32.5	65		**K5**	32.5	32.5	0	0	65
8	**K6**	0	0	0	0	0		**K6**	0	0	32.5	32.5	65
9	**K7**	0	32.5	32.5	0	65		**K7**	0	0	32.5	0	32.5
10	**K8**	32.5	0	32.5	0	65		**K8**	0	32.5	32.5	0	65
11	**K9**	32.5	0	0	0	32.5		**K9**	0	0	0	32.5	32.5
12	**K10**	32.5	32.5	0	0	65		**K10**	32.5	0	32.5	0	65
13	**K11**	32.5	0	32.5	0	65		**K11**	0	32.5	32.5	0	65
14	**K12**	32.5	0	32.5	32.5	97.5		**K12**	32.5	0	0	0	32.5
15		195	130	130	162.5	**617.5**			130	195	195	162.5	**682.5**
16													

Image 5.0 - Decision Variables Holding the Volume of Waste per Kabadiwala per Generator

The second set of decision variables, depicted in Image 6.0, were created in order to have a mechanism that allowed us to record whether or not a trip was made between a kabadiwala and a generator. Since we would be unable to use an ‘IF’ function in a linear solver model, we had to design a more sophisticated method of arriving at the same answer. Two matrices identical to the first set of decision variables were created for this purpose. This second set of decision variables were all constrained to be binary variables that could only take on the values of ‘1’ or ‘0’. If the value in the corresponding cell in the first set of decision variables was greater than zero, thus implying that a trip was made, this cell would take on the value of 1. If not, it would take the value of 0. The cells in the first binary matrix would be denoted by $B_{ij,}$ while the cells in the second binary matrix would be denoted by $b_{ij.}$ For instance, cell B3 is zero in the above image indicating that no trip was made. Therefore, cell B19 in the corresponding binary matrix would have to read '0'. For this, we introduced two constraints to this second set of binary decision variables:

i) The binary decision cell would have to be less than or equal to the value in the corresponding volume decision cell divided by five. The right hand side of this constraint was divided by five because kabadiwalas need at least 5 kgs of waste (minimum requirement) to make a trip. This constraint ensures that the binary variable cell is never more than 0 when the corresponding volume cell is less than 5 kgs, thus correctly implying that a trip was not made.

$$B_{ij} <= KG_{ij} / 5$$

$$b_{ij} <= kg_{ij} / 5$$

ii) The binary decision cell would have to be greater than or equal to the value in the corresponding volume decision cell divided by an extremely large number far higher than the maximum value that the cell would be able to take. This constraint was introduced to ensure that the binary cell would never be zero when it should be one, correctly indicating that a trip was made when the volume was higher than 5.

$$B_{ij} <= KG_{ij} / 10{,}000$$

$$b_{ij} <= kg_{ij} / 10{,}000$$

	A	B	C	D	E	F	G	H	I	J	K	L	M
17	Decision Variables - Binary Dummy Variables to Record whether a trip was made or not												
18	**Trip Counter 1-4**	**G1**	**G2**	**G3**	**G4**			**Trip Counter 5-8**	**G1**	**G2**	**G3**	**G4**	
19	**K1**	0	0	0	0	0		**K1**	1	1	0	0	2
20	**K2**	0	1	0	1	2		**K2**	0	1	0	1	2
21	**K3**	0	1	0	1	2		**K3**	0	1	0	1	2
22	**K4**	0	0	0	1	1		**K4**	0	0	1	1	2
23	**K5**	1	0	0	1	2		**K5**	1	1	0	0	2
24	**K6**	0	0	0	0	0		**K6**	0	0	1	1	2
25	**K7**	0	1	1	0	2		**K7**	0	0	1	0	1
26	**K8**	1	0	1	0	2		**K8**	0	1	1	0	2
27	**K9**	1	0	0	0	1		**K9**	0	0	0	1	1
28	**K10**	1	1	0	0	2		**K10**	1	0	1	0	2
29	**K11**	1	0	1	0	2		**K11**	0	1	1	0	2
30	**K12**	1	0	1	1	3		**K12**	1	0	0	0	1
31		6	4	4	5	**19**			4	6	6	5	**21**

Image 6.0 - Binary Decision Variables that Indicate the Incidence of a Trip

Incorporating the Distance Constraint

Since the kabadiwalas and generators are distributed on a grid with specified X and Y coordinates, the distance between them can be calculated using the following formula:

$$\mathit{sqrt}((\text{Generator } Y \text{ Coordinate} - \text{Kabadiwala } Y \text{ Coordinate})^2 + (\text{Generator } X \text{ Coordinate} - \text{Kabadiwala } X \text{ Coordinate})^2)$$

If a trip was made it means that the kabadiwala travelled the distance from his store to the related generator *and* made the trip back to his store. Therefore for each trip that was recorded (with a ‘1’ in the binary decision cells) the actual distance travelled was *twice* the distance indicated by the above formula. The total distance travelled by a unique kabadiwala is the sum of the distance travelled on each individual trip. On average, each kabadiwala cannot travel more than 15 kms on a daily basis. This upper bound was incorporated as a constraint to the model.

For instance, for K1, the constraint would be depicted as follows:

$$\sum_{j\,=\,1\text{-}4} ((B_{1j} * 2 * \text{Distance from K1 to } G_j) + (b_{1j} * 2 * \text{Distance from K1 to } G_j)) <= 15000$$

However, as the traffic in the city varies, this upper bound also tends to vary. When there is low traffic the kabadiwala can travel more whereas when there is high traffic the kabadiwala tends to travel less. Therefore this was one of the constraints that we varied in our simulations, as discussed later on in this paper. Image 7.0 depicts a snapshot of how this constraint was visualized. The first column is a sum total of the distance travelled by the kabadiwalas. This model also assumes that all kabadiwalas are similar in their capacity to travel and therefore have the same upper bounds.

Total Distance Travelled Constraint			
K1	8563.647506	<=	15000
K2	9782.80882	<=	15000
K3	8438.729033	<=	15000
K4	9151.156723	<=	15000
K5	9647.036863	<=	15000
K6	7569.961644	<=	15000
K7	9502.080456	<=	15000
K8	9956.654433	<=	15000
K9	8076.490226	<=	15000
K10	8400.706713	<=	15000
K11	9843.879789	<=	15000
K12	9806.378374	<=	15000

Image 7.0 - Table depicting the ‘Total Distance Travelled’ Constraint

Other Constraints

1) Maximum kabadiwala processing capacity - The total volume processed by each kabadiwala would not be able to exceed more than 150 kilos, the current average available capacity for kabadiwalas. The following formula depicts the constraint for K1:

$$\sum_{j = 1\text{-}4} (KG_{1j} + kg_{1j}) <= 150$$

2) Maximum generator production capacity - The average daily capacity of the generators was calculated to be 250 kgs based on the average number of households in each housing society, the number of people per household, and the volume of waste produced per person. The following formula depicts the constraint for G1:

$$\sum_{i = 1\text{-}12} (KG_{i1} + kg_{i1}) <= 150$$

3) Each kabadiwala would not be able to carry more than 32.5 kgs on each trip given the limitations of the vehicle they use. The following formula depicts the constraint for K1 on a potential trip to G1:

$$KG_{11} <= 32.5$$

Objective Function

The objective of this model is to maximize the total waste being processed, as characterized by the following formula:

$$\sum_{j = 1\text{-}4,\ i = 1\text{-}12} (KG_{ij} + kg_{ij})$$

Varying Constraints for Conducting the Simulation

Two constraints were varied to create different scenarios that could be simulated. First, the total distance that could be travelled by each kabadiwala was said to be dependent on whether the traffic during the day was low, medium or high. The following table shows the appropriate constraints.

	Maximum Distance Constraint (metres)
Low Traffic	20,000
Medium Traffic	15,000
High Traffic	10,000

Table 2.0 - Possible Values for the 'Maximum Distance Travelled' Constraint

Second, the waste generated by each generator was said to take two values. On any average day, each generator would produce 250 kgs of waste. However, on certain special occasions when the generator was having a celebration on their premises such as an 'Annual Day', the waste produced would increase by around thirty percent to 325 kgs.

	Waste Produced by Generator (kgs)
Average Volume	250
Surge Volume	325

Table 3.0 - Possible Values for the 'Generator Capacity' Constraint

Phase 3 Findings - Input Model Findings

We recorded various output data generated by the optimization model under the 48 different daily scenarios, specifically total amount of waste processed by the marketplace (Objective Function cell), waste volumes collected by individual kabadiwalas, waste volumes sourced through individual waste generators, distances travelled by kabadiwalas, number of trips taken by kabadiwalas, number of times a staff members at waste generators have to interact with rePurpose kabadiwalas. Summary statistics was then generated based on this raw optimization model data.

Overall, the objective function performed well across all 48 scenarios of this optimization model. The total amount of waste processed by the marketplace was exactly equal to the total amount of waste produced by the 4 generators. In other words, every piece of recyclable dry waste generated by the housing societies was collected by kabadiwalas in all scenarios, even in extreme circumstances where waste generation was "surge" for all 4 generators and the traffic setting was set to be the highest. This is important for the actual implementation of the optimization model since reliability and 100% collection rate is crucial for the retention of waste generators on the rePurpose platform in the long run.

Kabadiwala Processsing Quantity Constraints			
K1	65	<=	150
K2	130	<=	150
K3	130	<=	150
K4	97.5	<=	150
K5	130	<=	150
K6	65	<=	150
K7	97.5	<=	150
K8	130	<=	150
K9	65	<=	150
K10	130	<=	150
K11	130	<=	150
K12	130	<=	150

Table 5.0 - Under-utilization of kabadiwala capacity

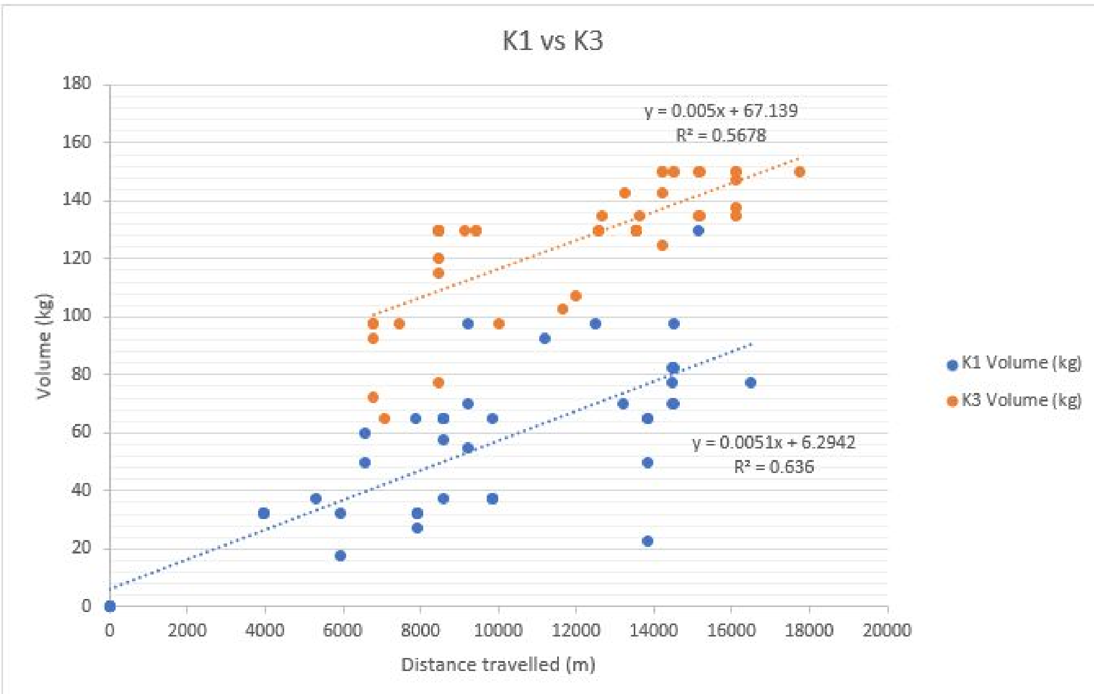
However, this performance could signal under-utilization of kabadiwalas' idle capacity. The table above shows the kabadiwala daily processing constraint under the most stress-tested scenario out of the 48 (high traffic setting & surge waste generation of all 4 generators), and none of the kabadiwalas are at capacity. In fact, only 28 out of the total 576 KG_{ij} variables are at capacity in the entire model. Even though this is outside the scope of this thesis, the level of this under-utilization can be tested by adding additional waste generators onto the optimization model and re-doing this analysis to check whether or not collection rates would remain 95-100% across scenarios with the same number of kabadiwalas.

Findings on Kabadiwalas and Effect of Traffic

Avg volume (kg)	Low traffic	Medium traffic	High traffic	All scenarios
K1	29.5	67.0	54.8	50.5
K2	119.2	112.8	98.6	110.2
K3	132.2	134.2	113.1	126.5
K4	114.8	113.9	99.7	109.5
K5	60.5	93.1	107.7	87.1
K6	135.0	111.1	91.1	112.4
K7	106.1	87.0	83.1	92.1
K8	88.8	91.3	115.2	98.4
K9	93.8	82.7	78.9	85.1
K10	128.6	109.2	100.0	112.6
K11	114.4	93.6	111.1	106.4
K12	27.2	54.1	96.7	59.3
Average K	95.8	95.8	95.8	95.8

Table 6.0 - Kabadiwala average daily waste volumes

On average, a kabadiwala in the current marketplace is collecting 95.8 kg per day from waste generators on the rePurpose platform. However, this amount varies significantly across different kabadiwalas located across the Bandra locality of Mumbai. Across all scenarios, the minimum average volume is with K1 at 50.5 kg/day whereas the maximum average volume is with K3 at 126.5 kg/day. This effect is largely a result of kabadiwalas' relative distances to its closest generators. High-earners such as K2, K3, K4, and K10 are the closest service providers distance-wise to their generators (G4, G2, G4, G1 respectively). On the other end, a low earner is either isolated from the whole grid (e.g. K1, K9) or isclose to certain generators on the grid but is not the closest kabadiwala to that generator (e.g. K12 who is being crowded out from G3 and G1 by K6 and K10).

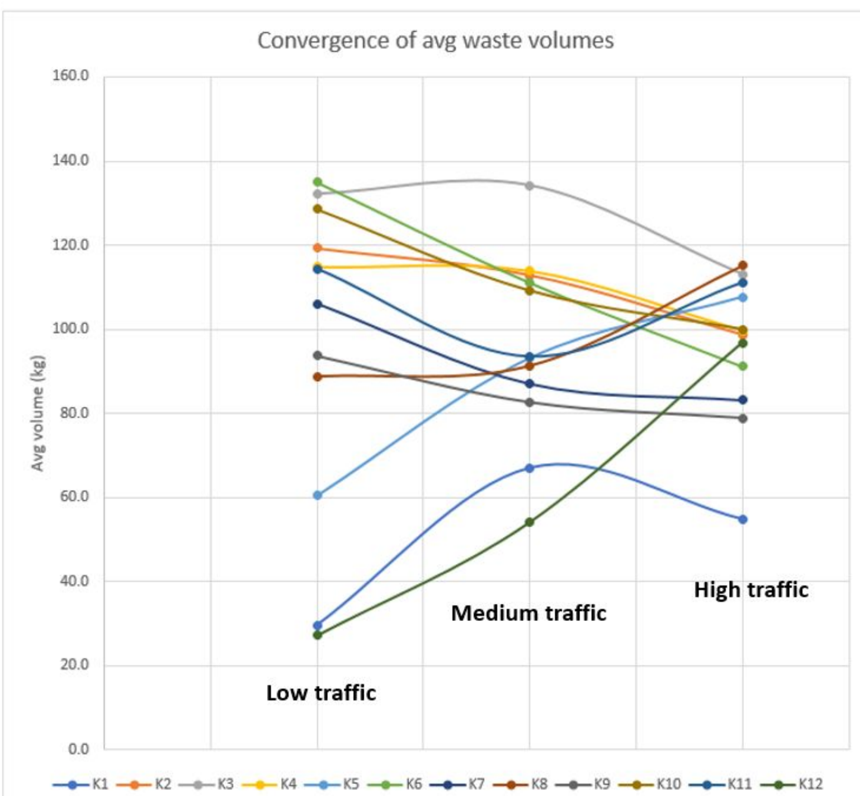


Graph 2.0 - Effect of Location on Kabadiwala Waste Volumes/Earnings

An example of this inequality can be perfectly demonstrated by the graph above. Both best-fit lines have almost identical slopes, meaning that both K1 and K3 are able to secure the same amount of waste for each additional meter travelled. However, since K3 is much more centrally located than K1 and is the closest kabadiwala to G2, its best-fit line's intercept is more than 60 kg larger than that of K1. This is a direct consequence of its endowed location.

This variance is detrimental for rePurpose's implementation since the waste secured by kabadiwalas on our platform is a direct proxy of the amount of additional income that kabadiwalas can make from our platform. Out of the 576 instances, there were 18 instances where a kabadiwala did not earn any volumes/additional income that day, 16 of which are attributed to K1 (6 instances) and K12 (10 instances). If this optimization model was used in practice, K1 and K12 will earn consistently 38%-47% less than the average. Given the kabadiwala community is a tight-knit one, especially within individual localities of Mumbai, this could create un-intended divisive effects within that community and potentially cause backlash from the community. As a result, further iterations of this optimization model would need to introduce a feature to smooth over the differences between kabadiwalas and guarantee a minimum level of waste volume granted to a rePurpose model to ensure equality.

Graph 3.0 - Effect of Traffic on Average Waste Volumes of Kabadiwalas



Interestingly, increasing levels of traffic has a positive side effect on smoothing over the aforementioned variances, contributing the equality of waste volumes given to kabadiwalas. As the system witnesses an increase in traffic (decrease in maximum distance that can be feasibly travelled by any kabadiwala) from low to medium and to high, the average waste volumes of kabadiwalas across waste generation scenarios converge. This occurs because as traffic increases, high-earners can no longer make as many trips to collect waste on a daily basis, enabling low-earners with idle capacity to scoop in and make more trips than they were previously doing to earn more volumes (same trend can be observed for the average # of trips graph). This trend can be observed for every kabadiwala (high earners switching places with low earners) except K1. Its average waste volume under high traffic is actually lower than under medium traffic because it is the most isolated service provider on the grid. High traffic severely limits its ability to make trips - in fact, its average # of trips decrease from 2.4 under medium traffic to 2.1 under high traffic.

Table 7.0 - Effect of Traffic on Intra-Kabadiwala Variances

Volume standard deviation	Low traffic	Medium traffic	High traffic	All scenarios
K1	35.3	22.2	18.1	30.1
K2	23.5	14.8	12.3	19.2
K3	24.2	11.0	20.7	21.3
K4	25.5	18.3	16.7	21.3
K5	41.0	41.3	24.5	40.8
K6	15.1	22.3	17.6	25.7
K7	25.6	23.8	16.8	24.1
K8	18.3	25.9	18.1	23.9
K9	30.5	20.1	17.2	23.7
K10	18.0	30.5	25.8	27.5
K11	16.9	22.2	23.3	22.5
K12	34.2	44.9	33.5	47.0
Average K	44.7	33.4	26.3	35.5

In addition to its effect on average waste volumes, traffic also reduces variance within each kabadiwala across the 16 waste generation scenarios in the aggregate. As seen in the table above, the standard deviation of kabadiwala waste volumes as a result of differing waste generation scenarios decreased from 44.7 kg under low traffic to 26.3 kg under high traffic.

However, even though it haphazardly suppresses unequal treatment of kabadiwalas, traffic as an exogenous factor is detrimental to the rePurpose marketplace in reality in two ways. First, with increasing traffic, kabadiwalas will potentially not be willing to take pick-up requests from waste generators outside their perceived radius of locations that are reachable given the traffic condition, thus harming reliability of the marketplace and retention of waste generators. Secondly, traffic affects the output side of the rePurpose marketplace as the waste is supposed to be collected by trucks and handed off to industry processors on a daily basis. Traffic may prevent rePurpose trucks from collecting all of the waste sorted from kabadiwalas on the marketplace or delivering on time to industry processors. Storing the bulky un-compressed waste overnight will not only incur extra expenses for rePurpose, but also harm retention rates of kabadiwalas and recyclers, which in turn has a peripheral impact on the reliability of the collection system from the point of view of waste generators.

Avg volume per trip (kg)	Low traffic	Medium traffic	High traffic	All scenarios
K1	26.5	28.7	27.1	27.4
K2	28.3	30.7	30.6	29.9
K3	29.3	29.7	30.7	29.9
K4	27.4	30.0	30.7	29.4
K5	26.9	30.9	30.2	29.3
K6	28.6	29.0	32.4	30.0
K7	29.4	30.4	30.9	30.3
K8	31.6	26.6	29.8	29.4
K9	29.3	29.3	31.6	30.1
K10	29.0	28.3	30.6	29.3
K11	31.3	28.6	32.3	30.7
K12	24.3	26.7	30.9	27.3
Average	28.5	29.1	30.7	29.4

Table 8.0 - Average Volumes per Trip to Waste Generator

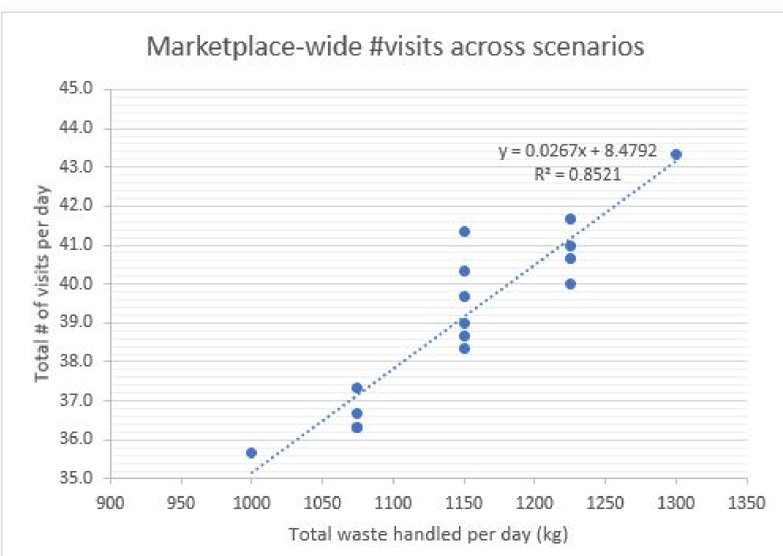
Last but not least, the optimization model performed well in terms of increasing the amount carried by each kabadiwala on a single trip to as close to the capacity of 32.5 kg as possible. The allocations ensured that each kabadiwala was carrying the maximum the person can carry, unless the model absolutely had to meet the remaining demand from certain generators that was not fulfilled by other kabadiwalas.

Findings on Waste Generators and Waste Generation Scenarios

As mentioned, 16 generation scenarios were created using every combination of two possible "states of the world" of an individual generator: average and surge. Given that the collection rate was 100% for every single generator in every scenario, the only relevant variable under discussion regarding waste generators is the number of visits by kabadiwalas per housing society on a daily basis. Breakdown by generation scenarios as follows:

G1 state	*Average*	*Average*	*Average*	***Surge***	*Average*	*Average*	***Surge***	***Surge***	*Average*	*Average*	***Surge***	***Surge***	*Average*	***Surge***	***Surge***	***Surge***	*All scenarios*
G2 state	*Average*	*Average*	***Surge***	*Average*	*Average*	***Surge***	*Average*	***Surge***	*Average*	***Surge***	*Average*	***Surge***	***Surge***	*Average*	***Surge***	***Surge***	
G3 state	*Average*	***Surge***	*Average*	*Average*	*Average*	***Surge***	***Surge***	*Average*	***Surge***	*Average*	*Average*	***Surge***	***Surge***	***Surge***	*Average*	***Surge***	
G4 state	*Average*	*Average*	*Average*	*Average*	***Surge***	*Average*	*Average*	*Average*	***Surge***	***Surge***	***Surge***	*Average*	***Surge***	***Surge***	***Surge***	***Surge***	
G1 avg #visits	9.7	8.7	8.0	**11.0**	9.0	9.3	**11.7**	**11.3**	**8.3**	8.3	**10.0**	**11.7**	9.3	**10.7**	**10.0**	**11.7**	9.9
G2 avg #visits	8.7	8.3	**11.3**	9.0	8.7	**10.3**	9.3	**12.0**	**8.7**	**10.7**	9.3	**12.0**	**10.7**	9.3	**10.3**	**11.0**	10.0
G3 avg #visits	8.3	**11.0**	8.7	8.3	9.7	**11.3**	**11.0**	9.0	10.0	9.0	9.3	**10.0**	**10.3**	**10.3**	9.0	**10.3**	9.7
G4 avg #visits	9.0	8.3	8.7	8.0	**10.0**	8.0	8.3	9.0	11.3	**10.7**	**11.0**	8.0	**10.7**	**10.3**	**10.7**	**10.3**	9.5
Avg G avg #visits	8.9	9.1	9.2	9.1	9.3	9.8	10.1	10.3	9.6	9.7	9.9	10.4	10.3	10.2	10.0	10.8	9.8

Table 9.0 - Number of Kabadiwala Visits per Generator

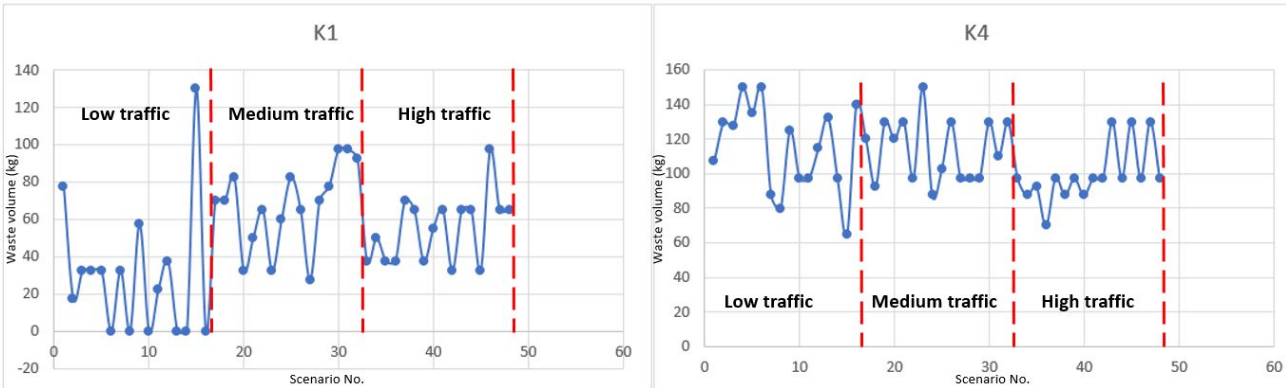


Graph 4.0 - Relationship between Total Visits and Total Waste Handled

The average number of visits range from 8 (minimum) to 12 (maximum), with averages across scenarios from 9.5 visits to 10.0 visits for the 4 housing societies. Predictably, the number of visits are higher during surge than average - for example, G1 has to entertain 10.7 visits on average from kabadiwalas during surge as opposed to 8.9 visits on average during non-surge. In addition, as demonstrated in Graph X.0, the total number of visits across the collection system increases proportionally with the total amount of waste handled by the system per day across the 16 scenarios (strong R-squared).

Having spoken to four housing society managers in Mumbai during the on-site interview phase, implementing this optimization model on the ground would not be feasible because entertaining 8-10 visits by multiple kabadiwalas as suggested by the solutions would not only be time consuming for staff members but also hard to manage in terms of kabadiwala' payments to the generators in exchange for the waste.

As a result, there are three ways to tackle this issue. First, rePurpose can set up two pick-up times, morning and afternoon, where different kabadiwalas can come during the same time to pick up waste from housing societies. This requires another optimization model managing the time slots of each kabadiwalas' workdays that links up with the current allocational model of matching kabadiwalas to generators based on location. Secondly, this current optimization model can be improved by removing the implicit constraint that each kabadiwala can only visit at maximum twice to any waste generator. This requires many more decision variables & constraints (768 decision variables), thus requiring more robust software to optimize for a problem at this scale. Thirdly, rePurpose could invest in faster and larger transportation vehicles (etc. motorized scooter as opposed to manual), increasing both kabadiwalas' carrying capacity per trip and their maximum distance travelled per day, thus reducing the number of visits from the point of view of waste generators.



Graph 5.0 - Variation between Waste Generation Scenarios & Traffic

Ultimately, Graph 5.0 demonstrates the effect of different waste generation scenarios given the traffic scenario. For K1, K4 as well as all other unlisted kabadiwalas in the optimization model, variations within the 16 generation scenarios given the traffic cause significant variance of the actual waste volume processed by each kabadiwala.

Phases 3 - Output Model Methodology and Findings

The input side model optimally allocates the waste from the generators to the kabadiwalas. The output side of our marketplace deals with the transaction between kabadiwalas and industry processors. However, there is no allocation issue on this side given that a) industry processors have extremely high capacities and can take in over 15 tonnes at a time and b) all industry processors closest to *Bandra* are concentrated within *Dharavi* and are next to each other.

The optimization in this link lies in best routing a truck with multiple stops at kabadiwala stores and then delivering this aggregated waste pool to the industry processors in bulk. In order to solve what was essentially a 'travelling salesman' problem, we used the mapping and routing software of Routific. First, the stakeholders distributed in the grid were transposed onto an actual map of *Bandra* and prominent locations near their corresponding coordinates were chosen, as summarized in Table 4.0.

Then these locations were fed into the routing software as the required stops to be made. The truck(s) would start at T-Junction, the entrance to *Dharavi,* and end their route also at the same place. The intuition here is that the industry processors are all located close to this location and that the truck would remain at this spot after delivering the waste until called upon the next day. A small size waste pickup truck can hold around 1 ton of uncompressed waste. Therefore, we would need two trucks to ensure that even at maximum waste generation by every generator (325 kgs * 4 = 1.3 tonnes), there is enough room in the trucks. Image 8.0 shows the optimal route for two trucks to take, starting and ending at T-Junction, making 12 steps along the way.

Kabadiwala	Corresponding Map Location
K1	Hill Road Society
K2	Bhabha Hospital
K3	Tea Villa Café
K4	Bandra Railway Police Station
K5	Bandra Reclamation MHADA Ground
K6	Maharashtra Mitra Mandal Library
K7	Candies
K8	Chimbai Rig
K9	Bahr Al Hikmah Masjid & Madrasa
K10	Lilavati Hospital & Research Centre
K11	Mumbai Shopping Cart Dot Com
K12	Pixie Dust Farm

Table 4.0 - Real Locations in Bandra based on Kabadiwala Coordinates

On an average day, the optimal solution shows Driver 1 picking up waste from four stops and Driver 2 picking up waste from eight stops. This solution, however, is limited by the capacity of the trucks matched with the output of the kabadiwalas it servicing. Driver 2 may not be able to pick up waste from eight stops if it entails eight kabadiwala stores with high volumes.

However, if the majority of the eight kabadiwalas held low volumes, as calculated by the input side model and recorded in our database, then the driver would have no capacity limitation. Therefore, this constraint needs to be in built into a more customized version of this routing problem for practical implementation. For instance, right now the optimal solution shows Driver 2 is servicing K5, K10, K1, K11, K8, K6, K7, and K12. Driver 1 is servicing K2, K3, K4, and K9. Assuming, for example, a scenario where all four generators had 'surge' production (325 kgs each) and that the traffic was high, only allowing for 10,000 total metres to be travelled by each kabadiwala, the combined volume of Driver 1's kabadiwalas would be 422.5 kgs and that of Driver 2 would be 877.5 kgs (using data generated by the input side model for the specified scenario). Allowing about 100 kgs in leeway for bulky objects, Driver 2's truck would narrowly accommodate all the required amount of waste. In this scenario it might be prudent to allocate one of Driver 2's stops to Driver 1 to be safe.

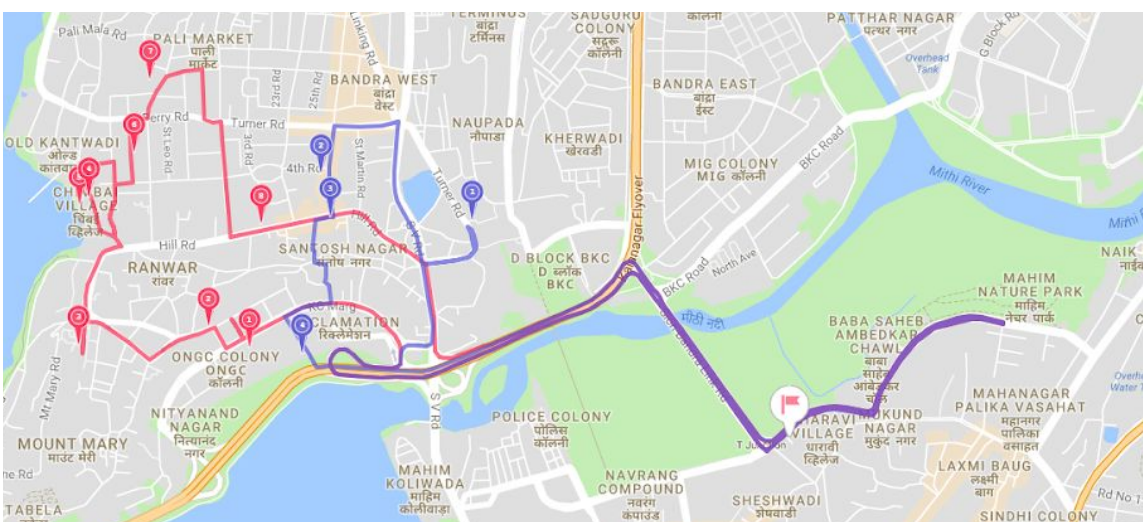


Image 8.0 - Optimal Route Taken by Two Trucks (Differentiated by Color)

CONCLUSION

It is apparent from both the literature review, and our own experiences in India, that efficient waste management is an urgent need in developing countries. The majority of existing systems administered by local municipalities are inefficient and only seek to remove waste from eyesight and dump it in landfills where it can go untreated for multiple decades. There is a clear correlation between economic growth and waste production; as developing countries increase their per capita GDP, the waste being produced in their urban areas also proportionally increases. Given the relative limitations of waste to energy incineration platforms and the unsustainability of dumping waste in landfills, the recycling industry, under today's circumstances, proves to be the most optimal solution. This paper provides an in-depth overview of Mumbai's informal recycling industry and the design for a marketplace model with the potential to increase the amount of waste recycled on a daily basis *and* ameliorate the livelihoods of small scrap dealers who tend to be impoverished and marginalized.

Going forward there are several important areas of further research to strengthen the existing data collected in Phases 1 and 2. First, Mumbai's supply chain issues, while similar to those in other parts of India, are still subjectively analysed and presented here. Similar primary data collection can be done in other urban cities across the world to better understand how this marketplace model can be adapted and scaled to best suit their specific needs. Second, the analysis of Mumbai here is in no way comprehensive but rather a representative snapshot of a section of the industry; there is scope for further research into the informal recycling sector in the city especially with regard to price variations between stakeholders.

Additionally, the models that were created in Phase 3 can also be enhanced. First, since the kabadiwalas were able to process 100 percent of the waste generated even in extreme ‘surge’ cases without hitting their own capacity constraints, a key takeaway is that we are thus able to onboard more generators to the platform without increasing the number of kabadiwalas. Second, further constraints need to be put into place to ensure that suboptimally located kabadiwalas are not systematically overlooked by the model, thus consistently receiving low volumes of waste. Third, this model assumes that all kabadiwalas are created alike with regard to the constraints on their transportation and processing capabilities. However, in reality there are slight variations between kabadiwalas that must also be taken into account when creating such a model. While this design is practical and realistic enough to be used in the pilot phase of the marketplace, a stronger back-end algorithm needs to be created when the platform starts to be scaled beyond its current scope.

REFERENCES

Agarwal, A., et al. "Municipal Solid Waste Recycling and Associated Markets in Delhi, India." Resources, Conservation and Recycling, vol. 44, no. 1, 2005, pp. 73-90, SCOPUS, www.scopus.com, doi:10.1016/j.resconrec.2004.09.007.

Aleluia, J., and P. Ferrão. "Characterization of Urban Waste Management Practices in Developing Asian Countries: A New Analytical Framework Based on Waste Characteristics and Urban Dimension." Waste Management, vol. 58, 2016, pp. 415-429, SCOPUS, www.scopus.com, doi:10.1016/j.wasman.2016.05.008.

Baishya, P., and D. K. Mahanta. "Improvised Segregation of Recyclable Materials in Guwahati City, India : A Case Study." Clarion: International Multidisciplinary Journal 2.2 (2013): 46-52. Web.

Bhaskar, A., and P. Chikarmane. "The Story of Waste and its Reclaimers: Organising Waste Collectors for Better Lives and Livelihoods." Indian Journal of Labour Economics, vol. 55, no.4, 2012, pp. 595-620, SCOPUS, www.scopus.com.

Chatterjee, P. "Child Ragpickers in India and Violation of Their Human Rights." European

Researcher 912.2 (2015): 155-62. Web.

Dalal, K., F. Rahman, and B. Jansson. "The Origin of Violent Behaviour among Child Labourers in India." Global Public Health, vol. 3, no. 3, 2008, pp. 77-92, SCOPUS, www.scopus.com.

Hunt, C. "Child Waste Pickers in India: The Occupation and its Health Risks." Environment and Urbanization, vol. 8, no. 2, 1996, pp. 111-114, SCOPUS, www.scopus.com.

Nandy, B., et al. "Recovery of Consumer Waste in India - A Mass Flow Analysis for Paper, Plastic and Glass and the Contribution of Households and the Informal Sector." Resources,Conservation and Recycling, vol. 101, 2015, pp. 167-181, SCOPUS, www.scopus.com, doi:10.1016/j.resconrec.2015.05.012.

Ravindra, K., K. Kaur, and S. Mor. "Occupational Exposure to the Municipal Solid Waste Workers in Chandigarh, India." Waste Management and Research, vol. 34, no. 11, 2016, pp. 1192-1195, SCOPUS, www.scopus.com, doi:10.1177/0734242X16665913.

Suthar, S., P. Rayal, and C. P. S. Ahada. "Role of Different Stakeholders in Trading of reusable/recyclable Urban Solid Waste Materials: A Case Study." Sustainable Cities and Society, vol. 22, 2016, pp. 104-115, SCOPUS, www.scopus.com, doi:10.1016/j.scs.2016.01.013.

Yedla, S., and S. Kansal. "Economic Insight into Municipal Solid Waste Management in

Mumbai: A Critical Analysis." International Journal of Environment and Pollution, vol. 19, no. 5, 2003, pp.516-527, SCOPUS, www.scopus.com.

Zia, H., V. Devadas, and S. Shukla. "Assessing Informal Waste Recycling in Kanpur City, India." Management of Environmental Quality, vol. 19, no. 5, 2008, pp. 597-612, SCOPUS, www.scopus.com, doi:10.1108/14777830810894265.

"Cooling Agents: An Examination of the Role of the Informal Recycling Sector in Mitigating Climate Change." Chintan Environmental Research and Action Group, 2009. Web.

"On the Road to Zero Waste: Successes and Lessons from Around the World." Global Alliance for Incinerator Alternatives, n.d. Web.