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Underground capsule pipeline logistic system

Feasibility study of an urban application

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Abstract

A feasibility study of an underground capsule-pipe system for storing and transporting small items and waste is presented. “Hyperloop for packages” for the last/first/mile/yard all the way to and from the final user in apartments and establishments. In many cases, one capsule of 2 kg can do the same job as a car with 1000 times larger mass. The conclusion is that such a system is technically feasible and economically good for all stakeholders. In one scenario, 30% less traffic and CO_2 and freed space was valued more than system cost. Still, society is not yet prepared and unaware of the possibility. The storybook Pipeville 2030 and a scale model of capsule-pipe logistics in LEGO were created to visualize and play around with during workshops, surveys, and story writing. Results from the first survey and Lisa’s user story are presented. Finally, areas for future research are suggested.

Peer review under responsibility of the scientific committee of the Transport Research Arena (TRA) Conference

Keywords: Urban planning; City logistics; E-commerce; Automatic micro-fulfilment centres; Circular economy; Waste removal

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1. Background and motivation

With the Green Deal, Europe commits itself to be the first CO_2 neutral continent by 2050 and to have reduced CO_2 emissions by 55% by 3030. For the road sector, the target for 2030 is a reduction of 30% in the EU and 70% in Sweden. 2/3 of the emission of climate gases occurs in cities. Analyses have revealed that changing the behaviour of transport users and current technologies alone will not be sufficient. Innovations and new technologies are needed to achieve the goal of the Paris Agreement and the EU's Green Deal.

In the world, each year 3 million die due to air pollution, mainly from motor vehicles in cities. Another 1.2 million dies in road traffic accidents, and in cities it is mostly unprotected road users. To this should be added the noise from motor vehicles in cities causes significant health problems.

Citizens are increasingly realising that the street space could be used for other things than cars, and many cities are implementing car-free or at least climate zones. This trend got further momentum during the lockdowns under the Corona pandemic. The concept of the 15-minute city stresses the importance of arranging access to services within short walking and biking distance.

A large share of mobility of persons is due to the need to move smaller items. E.g., take the car to the supermarket, the shop, the pick-up location for things bought on the internet, or to the waste and recycle site, which means a 2000-ton vehicle for moving a few kg goods. E-commerce is expected to increase its market share considerably for all types of goods, and there are many proposals on handling the related transport challenges (WEF 2020). However, most pilots with urban consolidation and micro-hubs for load-pooling have not been successful, partly because the customers demand fast delivery and the many difficulties with sharing data among competing companies. Night docks, parcel lockers, and smart door locks make it easier to deliver even when the receiver is not present. Cargo bikes and delivery mopeds are labour intensive and demand street space. Small automatic pods on the sidewalks annoy pedestrians, and drones in the air are noisy, weather sensitive, and not energy efficient.

To improve sustainability, there is political pressure to increase the re-use and the live of packaging, products, components, and materiel (Ellen MacArthur Foundation 2021). These circular flows require more transport than today's linear flows. Several initiatives make waste collection and handling less annoying, e.g., using Automated Vacuum Waste Collection (AVWC) systems. Waste is sorted in 2-4 fractions, placed in plastic bags, and then in a terminal. From there, the bags are sucked with under-pressure in pipes to a terminal outside the city. Thereby some but not all garbage trucks and waste bins on the sidewalks are eliminated. In Singapore, such waste removal systems are required by law for all new residential developments and subsidies are given to install them in old districts. The drawbacks are that such systems cannot take all waste fractions and that the bags too often break and glogg the system resulting in a bad smell (Farré 2021).

From the above, it is understood that there is room for improvements. This paper reports on a feasibility study to solve or at least mitigate these challenges and drawbacks of current technologies by introducing an underground capsule-pipe transport and storage system. It is a new mode of transportation with its own conveyance infrastructure. Relatively expensive to install, but like Internet, the cost for operating it is very low.

2. Previous research on capsule pipelines and underground logistics

During the last three years, we have collected and analysed over 2000 articles, reports, and patents and participated in some 50 conferences of relevance for the research area. One trend we observed has been to move the transport of water, sewage, gas, rail subway, district heating, electricity, telecom, and lately also vacuum waste collection underground to free up street space, as illustrated in Figure 1. In some cases, these technical infrastructures, including vacuum waste collection, are co-located into multi-utility tunnels or infra-culverts (Bergman 2022).

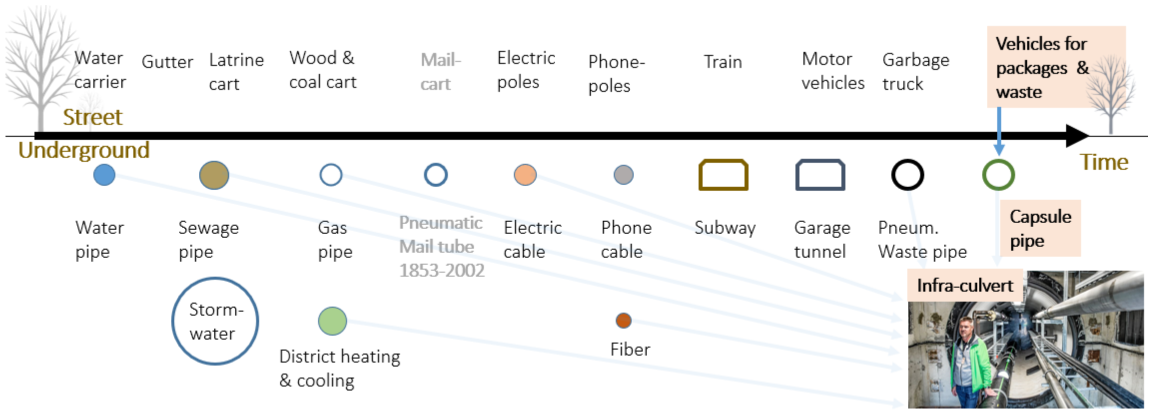


Fig. 1. Capsule pipeline continues the trend to move transport underground that started 2000 years ago

The first underground transport of mail in capsules in pneumatic mail tubes opened in London in 1853, and some 43 large cities followed. The competition from automobiles, e-mail, and their inability to carry larger items than letters caused their closure (Howgego 2022). Pneumatic Tube Systems are today used in most hospitals (Stanford 2010) for transport of samples to laboratories, blood bags to surgery, and lately also pharmaceuticals to nursing wards. They are also used in retail and banks for transport of money, and in industry for transport of samples and instruments.

Several underground freight transport systems have been proposed for load units that are considerably larger than the capsules in Pneumatic Tube Systems as sea containers and EU pallets, e.g., Carco Sous Terrain, Cargocap, PipeNet, MagWay, and Cargoloop. Complete Urban Logistics Systems have been investigated for Beijing (Hu 2021), Tokyo, New York, and the Netherlands. Visser 2018 made a comprehensive overview of these projects. Most failed mainly because of difficulties in attracting enough freight volumes to pay for the high cost of infrastructure investment and lack of interest from public authorities. This despite their high potential to reduce congestion on roads and streets, energy demand, CO_2, and harmful emissions. All these projects are designed to transport goods only between logistics terminals, but not the last 100 meters to and from the user of the goods, not inside buildings, and are rarely used for both goods and waste.

We have found only one person, DeDomenico 2022, who is developing an underground capsule-pipe system for transport of small items and waste in cities. It is called CargoFish and fulfils similar services as ours, but with the difference that each capsule has an electric motor driving metal wheels that also get electricity from two rails on the inside of the 8-inch tube - one above and one beneath, while our system uses a combination of pneumatic and electromagnetism to propel and steer the capsules. We have not found any proposed system designed to both transport, store, and sort goods using the pipes, which our proposed system is designed for.

3. Purpose and research questions

The purpose is to make a feasibility study regarding the development and deployment of underground capsule-pipe systems that is open to the public for storing and transportation of small items and waste in cities and in buildings.

Research questions to be addressed:

- Is it technically feasible to build such system? What further developments are needed?
- For what will citizens use such system? At home? At work?
- What are the pain-points, risks, and challenges? How can these be mitigated?
- What are the benefits? How much are different users willing to pay?
- What is the cost to install? To operate? To maintain and repair?
- Is it economically feasible? For each stakeholder in the eco system?
- What are the knowledge gaps to be addressed in future works?

4. Research design and methodology

We investigated used and proposed technologies for capsule-pipelines, and we found that the one used in hospitals is the most suitable to be adapted. The first design of such a logistics system was made, and we interviewed about 40 people about using such system in their daily life at home and at work. The findings were synthesised into about 25 personas and documented in a booklet called Pipeville 2030.

A LEGO-model of Pipeville 2030 with a capsule-pipe system was built to enable communication. The idea is that decision-makers and stakeholders will use the model in several ways in workshops. It will be displayed at several conferences as background for surveys. We have secured a place in the exhibition at TRA for displaying it.

5. Research results

5.1. Technical feasibility

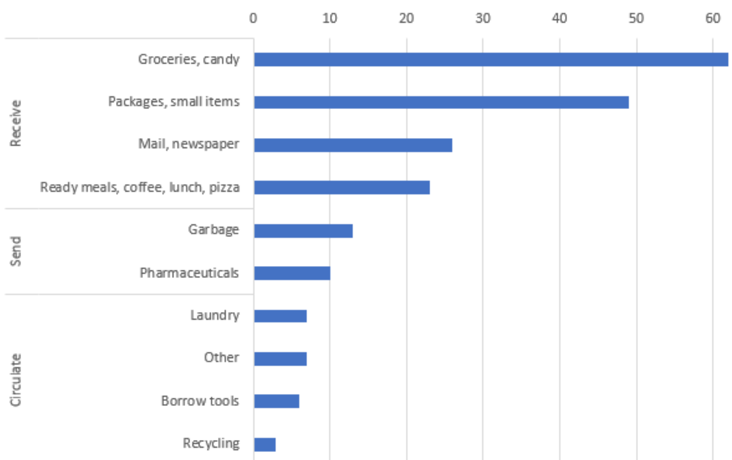
We call the capsule-pipe technology used for letters 1853-2002 for version 1.0. The one used in most hospitals today for version 2.0. The one in this study for version 3.0. Version 4.0 refers to systems where the lift and propulsion of the capsules solely are performed by electromagnets, e.g., PipeNet. Version 5.0 refers to systems where the pipes are emptied of air so that the energy consumption for propulsion is reduced, e.g., Hyperloop as E. Musk has proposed.

From the stories in Pipeville 2030 about 30 generic use cases were identified with the following requirements: the outer diameter of the tube must be increased from 160 mm in hospitals to around 300 mm in order to ship boxes, e.g. for shoes, it must be easy and safe to use by the general public, it must be integrated with the other modes of transport, it should be designed for both storing and transportation and for a much wider range of goods, and it should use electromagnets as a complement to pneumatics to considerably reduce cost and downtime. Based on these requirements, we made a second design, including many innovations. During two years of iterations, sprints as called in agile development methods, a comprehensive system was developed and described in several patent applications. The latest application has 35 pages and 38 claims. Then we know that it is technically feasible.

5.2. Results from the first public user survey

The LEGO model of Pipeville 2030 was displayed at a LEGO-exhibition May 7-8, 2022, in Varberg, Sweden. About 5 500 visitors and 81 filled in our survey using the Menti online platform. Before they answered, they got a 1–2-minute presentation, and those who filled out the survey got a bag with Jelly Bean candies and a straw for sucking the beans into the mouth to simulate a capsule-pipe system as gift to accompanying children. Results from the survey are shown in Tables 1-4. We asked for age, occupation, and type of neighbourhood they live in. We found that the respondents well represented the society. The average cost per month at work and at home they were willing to pay was 72 €, which confirmed our theoretical calculation of a payback time of around 1 year.

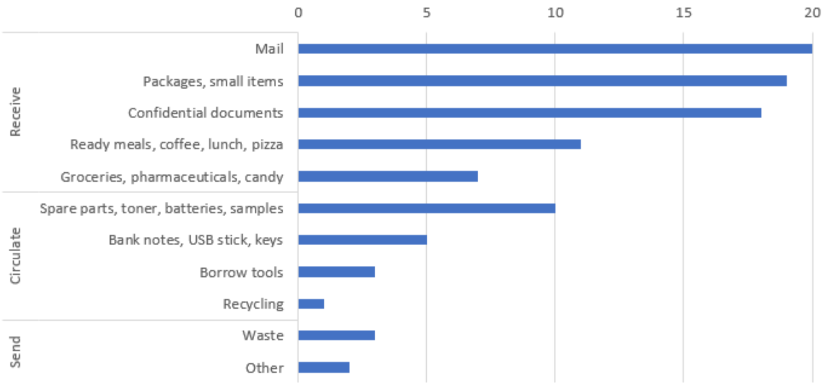
Table 1. What things will you send or receive most of in a capsule terminal at home? (206 answers)



What cost per month for a subscription are you willing to pay to be able to send and receive things in a capsule terminal at home?

Min 0,2 € Max 100 €
Average value 24,4 €

Table 2. What things will you send or receive most of in a capsule terminal at the workplace? (99 answers)



What cost per month for a subscription do you think your employer is willing to pay to be able to send and receive things in a capsule terminal?

Min 0 € Max 1000 €
Average value 121 €

Table 3. What are the biggest pain points, risks and challenges you see with capsule-pipe in cities? (57 answers)

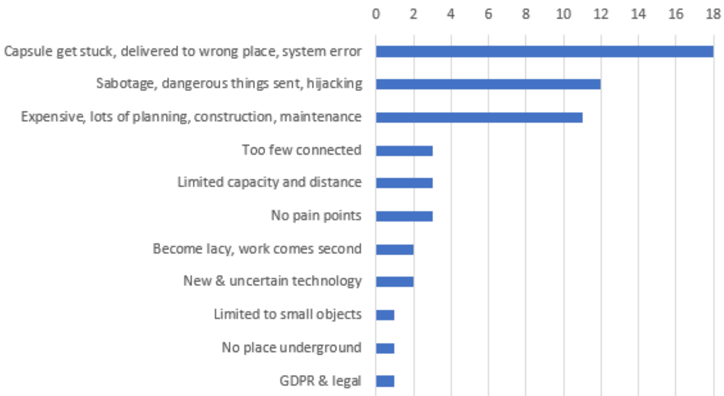
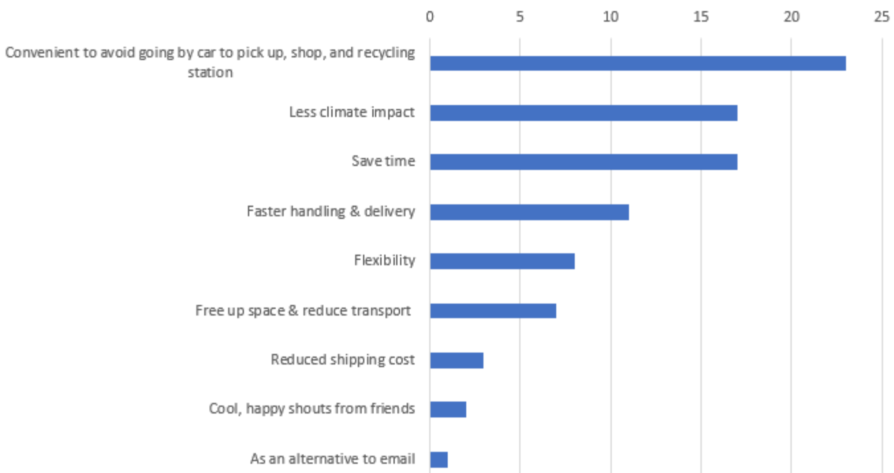


Table 4. What would be the most significant benefits for you with capsule-pipe? (89 answers)



5.3. Mobility of goods and people in Pipeville 2030 – illustrated by one day in Lisa's life

Based on the use cases in Pipeville 2030 and the results from the above survey, we wrote the story "One day in Lisa's life" to illustrate how the capsule pipe system could be used at home.

Lisa, 27 lives by herself in an apartment in the city district Pipeville. She moved there because she is passionate about sustainability, buys or borrows most of what she needs online, is keen to circulate and share as much as possible, and does not own a car. The district was inaugurated in 2030 and was the first in the world to have a capsule-pipe system pre-installed that connects all apartments and workplaces.

We follow her one day in her life. She wakes up and goes to the bathroom. Throws the dirty underwear in the laundry capsule and showers. She takes the last drops of shampoo and stuffs the empty bottle into a capsule for reusable packaging. She gets dressed and tells the smart speakers she wants a cardamom bun and a cappuccino. When Lisa takes out her overnight oat with raspberries from the fridge, the sound from the capsule terminal announces that the hot bun has arrived simultaneously as the espresso machine signals that her coffee is ready.

At lunch, she intends to visit her grandfather Charles, 87. He has homecare, which is responsible for ensuring that he receives hot food and medicines delivered three times a day via the capsule-pipe system. She asks the speaker what her grandfather will get for lunch, and the answer is pancakes. Lisa wants to surprise him and changes the order to two portions of grandfather's favourite dish, meatballs with lingonberry jam. When Lisa and Charles have finished eating, they sort his waste into inner capsules, one for each of the twelve different fractions prescribed by the city. She places the inner capsules in two capsules and sends them away from Charles' terminal.

In a drawer, Lisa finds eight old mobile phones. They agree to send them to the Red Cross, which then sorts out those that can be sold directly, those that should be repaired and then sold, and those that are going to the reverse factory for disassembly. She then takes Charles out on a wheelchair walk and notes that the city has finally replaced the trash bins in the park with self-emptying ones with capsules and with connection to the pipes.

For the evening, she has invited some friends to celebrate her birthday. Lisa likes shoes and has about 100 different ones in her shoe wardrobe in the capsule-pipe underground storage. It can deliver desired shoes directly to her apartment in less than 5 minutes at any time of the day. Before tonight's party, she has ordered two pairs of new shoes from shoes.vn, and two from the local rent-a-shoe.com. These shipments have reported that they are waiting in the pipe under the street. Those from Vietnam had arrived at the airport five hours earlier where the package had been placed in a capsule for direct delivery to Lisa, without intermediate terminals and completely automatically. For distribution with capsule-pipes, there is no need for deconsolidation, sorting, or consolidation into load units because one capsule only contains one SKU (Store Keeping Unit). When Lisa gets home, she calls up to her kitchen terminal the four shoe pairs waiting and four blue pairs from her own pipe wardrobe. She tries all of them on, chooses one pair, and returns the others. Five minutes later, a pling in her mobile tells her that both e-retailers have paid back the deposit to Lisa's bank account after a small deduction for the try-on service.

She starts cooking the main course but discovers that she is missing two eggs. Easily fixed, she just tells the speaker, and a few minutes later two eggs arrive in a capsule from the fully automatic convenience store. It consists of tubes with different temperatures where food is stored in capsules, short-term parking for a narrow range of products under the city district and long-term parking for a wide range of products further away. The prepacked capsules have arrived at the store directly from the farm or factory in the same way as the shoes from the airport. Hence no need for physical stores or distribution centres for order picking and packing.

When setting the table, she tries to pull out the table extension but realises it is hanging loose. A special bolt wrench is needed that she does not have. She shouts angry to the speaker to urgently send her a set of bolt wrenches. They arrive from the local tool library, and the table is ready just a minute before the guests arrive.

During the dinner, her guests select some bottles of wines from the wine club that Lisa is part of. They are stored at the agreed temperature in the remote pipe storage. For dessert, everyone orders his favourite from one of the 25 restaurants that offer delivery within 15 minutes. The capsules with deserts travel at reduced speed to avoid damaged and wait for each other in the pipes. When all have arrived, they simultaneously move to Lisa's kitchen. She places them on plates and returned the protective packaging in the same capsules as they arrived in.

After dinner, Lisa scrapes the leftover food from the plates into the waste grinder equipped with a dedicated capsule. Before she goes to bed, she visits the toilet and does number two. The faeces fall into a dedicated capsule. All capsules with faeces and waste are vacuum sealed before transport to the district's biogas plant. Hence, no need for a sewage treatment plant. Phase shifting salt stores the surplus heat from the plant and small balls store biogas at 800 atmospheres pressure. The melted salt and biogas balls are transported back to the city in the capsules. Biogas or hydrogen can also be transported in the same pipes as the capsules and hence used for propulsion instead of air. Residues from the plant containing phosphorus and other fertilizers are returned in capsules to the farms.

Heat exchangers, heat pumps, salt heat storage, gas tanks, and fuel cells are placed in the underground hubs that are connecting the pipes. In the hubs, the air is conditioned before it is sent, in the same pipes as the capsules, to the rooms in the buildings for heating, cooling, and ventilation services. Hence no need for radiators or air conditioners in the rooms, and less energy losses can be achieved, e.g., by transferring the residual heat from heat pumps for freezers in grocery stores to apartments in need of heating.

Before Lisa falls asleep, she thinks about how convenient it is that e-shopped goods can be delivered to the home at any time of the day with minute precision and not have to rent a car to take the waste to the recycling station outside the city district. She reflects on all the positive things her friends mentioned during the dinner, namely how convenient it is to borrow clothes, toys, and tools from each other or from the libraries and to store the winter clothes and frozen food in the pipe storage instead of in the apartment. They also appreciated how easy it is to send gadgets and clothes for repair, for cleaning or to second-hand buyers. Many had also freed space by getting rid of some closets, cupboards, and the washing machine, and switched to a smaller combined fridge and freezer.

In Pipeville, the dominant modes for personal mobility are walking, biking, autonomous pods that are called up when needed, and, if they are in a hurry, a taxi-drone for air transport. Items too large for the capsule, which has a standard diameter of 300 mm and a length of 600 mm, are transported by autonomous freight pods on the streets or in underground pod culverts. Under the city, there are culverts with pipes for water, sewage, district heating/cooling, capsules, and gas, together with cables for electricity and fibres for telecom. Co-location of these technical infrastructures in infra-culverts costs more to install than traditional methods. Still, it saves costs in the long run since maintenance, repair, replacement, and installing future technologies is done without digging up the streets.

The latest measurements show that in Lisa's district, each inhabitant emits on average 760 kilos less carbon dioxide compared to a person in a similar district without capsule-pipes used to emit 2022 and 300 kg less than today 2030. In addition, the capsule-pipe system makes it possible to use the street space for other purposes than cars, such as plantings, playgrounds, and outdoor cafes. Simultaneously it offers better access to physical products and services for all - regardless of age, health, income, ethnicity, or gender. Where Lisa lived before, most of the street space was used for car parking, garbage bins, and for traffic of cars, vans, delivery mopeds, and garbage trucks. She does not miss the noise, stress, or the harmful emissions. Lisa smiles and falls asleep sweetly.

Thomas, the doubter, who also was at Lisa's party, slept very restlessly and had nightmares. Someone had sent him a capsule containing anthrax. As a result, he became seriously ill, and the entire capsule-pipe system was forced to shut down for 14 days for cleaning. In another nightmare, companies had installed capsule-pipe systems with different specifications so they could not be connected and without any safety and security regulations from the authorities. These not-so-trustworthy companies recorded everything Thomas had received, sent, and threw away, including the weight of his faeces. They then resold the data even to those that had shady intentions.

5.4. Economic feasibility

We designed a simple Excel model and used data from a small town of 40 000 persons to analyze costs and benefits. We assumed that a capsule-pipe system costs 2 400 EUR to install per user if 50 persons share one user station. This is twice the cost of a pneumatic waste collection system. Some result from one scenario is shown in Table 5.

Table 5. Economic benefits per user in SEK in one scenario.

Service\Benefit per user	Vehicle km/year	Transport-cost/year	Space saved sqm	Rent for space/year	Cost reduct./year	Pay back year
Waste remowal	7	9	0.21	16	25	96.0
Distribution of mail & newspapers	251	359	0.76	60	419	5.7
Delivery of merchandisers	528	756	1.60	126	882	2.7
All services based the system	2 048	2 255	5.00	375	2 630	0.9

Additional results from the cost-benefit analyses were:

- The value of the saved space is most often larger than the investment cost of the system
- It is profitable to install a user terminal in a kitchen if the investment cost is less than 40 000 EUR
- 2 000 less vehicle*km/year means 30% less traffic
- Emissions of CO_2 were reduced by 760 kg/year and user, which is 30% of per capita CO_2 in Sweden

The following benefits were not included in the results above:

- less emissions: CO_2, noise, and harmful particles
- better service: the user can decide when and where to pick up a shipment and it can be delivered all the way to the user, e.g., in an apartment, office, or establishment
- storage services: capsules with items can be automatically stored, sorted, and retrieved and hence replace some wardrobes, freezers, parcel lockers, micro-fulfillment centers, and even complete retail stores
- circular economy services: it enables the circular flow of reusable packaging and products, borrowing, sharing, refurbishing, and collecting more and cleaner fractions of waste for recycling. It also enables automatic libraries of toys, tools, and clothes for lending

6. Conclusion and suggestions for future works

Even though the proposed urban capsule pipeline system seems technically and economically feasible, societies are not yet prepared. The concept is not yet known by researchers, policymakers, and city planners, and a regulatory and institutional framework is not yet in place. Furthermore, the capsule-pipeline system will co-exist with current and future technologies for transport and storage. Some research questions identified during the feasibility study:

- What planning, legal, and institutional framework is needed for installation and operation?
- What business models for the actors in the future ecosystem?
- How to integrate capsule-pipe systems with other logistics systems?
- What is a city's best mix of transport modes? For different types of cities as density, a mixture of workplaces, residences, commercial areas, green field or brown field, and year in the future?
- Start with transport inside buildings, e.g., shopping center as now in hospitals? Between courtyards? Between cities and major airports and seaports?
- Where best to place terminals? The courtyard between the houses, the entrance, the shop, or the kitchen?
- How far upstream the supply chain should it be used? All the way to the place of production or the farm?
- Is it cost-effective in the long run to invest in infra-culverts underground and multi-shafts in buildings at all new city development projects to be flexible for future technologies, e.g., capsule-pipe systems?
- Is it recommended to install a capsule-pipe system already before the building period?
- When to replace sewage treatment plants with mandatory toilets and garbage grinders using capsules?
- How to design ventilation, heating and cooling systems using the same pipes as the capsules?

To achieve all this, it will be necessary to establish a cluster of researchers and a forum with all the relevant stakeholders to develop and test prototypes of the components of the proposed system, demonstrators for active citizen involvement, pilots, a full-scale system in a new city development, and scaled up deployment.

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