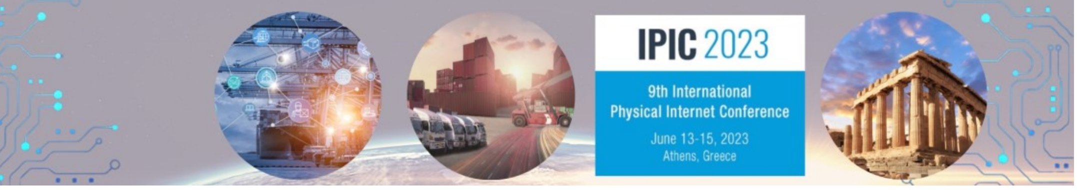

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Sten Wandel
Lund University, Box 118, Lund 221 00, Sweden
Corresponding author: sten.wandel@tlog.lth.se

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Vehicles on streets dominates last-mile transport. With increased e-commerce congestion, emissions, and cost increase. Delivery boxes and sidewalk robots reduce cost, but congestion prevails. Air drones reduce congestion but cannot take the expected volumes and are weather sensitive. Water and rail are not omnipresent. Underground pipes are used for transport of water, sewage, and gas, and was 1853-2002 used for transport of mail in capsules in 44 large cities. Pipes are now used in hospitals for capsules with test samples, blood, and medicine.

This project explores reinstallation of capsule pipelines for the general public. It reduces traffic and operating cost. It can accommodate very large volumes but requires large investments in infrastructure. A 5 kg capsule can, in many cases, automatically do the same job as a motor vehicle with 500 times larger mass and a driver. In one scenario, 30% less traffic and CO2, the freed space paid for installation of the whole system 1.6 times, and cost reductions resulted in a payback period of less than one year. The pipes can also be used for storing which reduces need for space in buildings and enables automatic retailing.

Finally, recommendation for further R&D are proposed.

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Last/first/mile/yard transport; Capsule as package/unit-load/vehicle; Automatic micro-fulfilment centers; E-commerce; Waste removal; City logistics; Urban planning; Circular economy; 15-minute City; Climate Impact

R c I

autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms); business models & use cases; interconnected freight transport; distributed intelligence last mile & city logistics; logistics and supply networks; Modularization; omnichannel & e-commerce logistics; PI implementation; vehicles and transshipment technologies.

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Select the most relevant area for your paper: ☒ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☒ Governance.

1 The challenges for Urban Logistics

Researchers agree that current technologies will not be sufficient to achieve the Paris Agreement or the goals of Fit for 55. Each year 3 million die due to air pollution, mainly from motor vehicles in cities. Citizens are increasingly realizing that the street space should be used for other things than motor vehicles, and many cities are implementing car-free zones. The concept of the 15-minute city requires arranging access to services and products within short walking or biking distance. A large share of mobility of persons is due to the need to move smaller items and not people. About 45% of car trips in cities are for that mission. It is a pressure to increase the re-use and the life span of packaging, products, components, and materiel. Such circular flows require more transport than today's linear flows. Storage of things, food, and waste occupy a considerable part of the space in buildings both in apartments, retail stores, and workplaces.

2 The state-of-art

2.1 Urban Logistics

For last-mile transport, cars and vans on streets are dominating. With the expected growth in e-commerce and circular economy, congestion and operating cost will increase. Cargo bikes and delivery mopeds are labor intensive and demand street space. Lockers and sidewalk robots can reduce labor cost but does not reduce need for space. Air drones can reduce street congestion but cannot take the expected volumes, are weather, and has a high operating cost. Water and rail are not available everywhere. Most pilots with urban consolidation and micro-hubs for load-pooling have not been successful, partly because the customers demand ever faster delivery and difficulties with sharing data among competing companies.

2.2 Underground Logistics

Several underground freight transport systems have been proposed with tunnel diameters of 90 – 250 cm. Wikitia 2023 reports on the following:

- *CargoCap[15] is a German company launched in 2002 under the direction of Prof. Dr.-Ing. Dietrich Stein. It promotes a freight system capable of transporting capsules containing two euro-pallets through 2.0 meter (6 feet) diameter tunnels or pipes, over distances up to 150 km (90 mi).[9][16]*
- *Mole Solutions Ltd.[17] is a British company founded in 2002 aimed at developing underground logistics systems or freight pipelines. It has developed a demonstration project in Cambridgeshire, UK featuring a 1.3 m (4 feet) diameter pipe equipped with rails and linear induction motors.[18][19][20][21]*
- *FoodTubes[22] ("Really fast food") was a 2008 British proposal by Noel Hudson for a 1.2 m (4 feet) diameter polyethylene tube system through which 2 m long capcules would travel at speeds up to 60 mph, powered by air pressure. It would be a packet-switched-style network connecting food producers and retailers. Costs were estimated at 5 million euro per kilometer. [8][7][23][24][25]*
- *Urban Mole was a 2009 concept for the transportation of packages through urban sewer systems.[26]*
- *Cargo Tunnel[27] was a concept published in 2009 by Russ Tilleman et al. They envisioned a 4-feet (1.2 m) diameter tunnel network connecting homes and*

businesses, enabling automated delivery of cillindrical packages up to 18x18 inches (45x45 cm). Delivery would take place through access cabinets, each equipped with an elevator to access the tunnel system.[10][11]

- *Cargo Sous Terrain is a planned system to complement the Swiss road and rail network, in development since 2013. It will feature 6.0 meter diameter tunnels and transport euro-pallets and shipping containers.*[28]
- *Magway*[29] *is a British start-up founded in 2017 aimed at developing a pipe network for the delivery of packages to consumers and businesses. It plans to use small HDPE pipes with a diameter less than 0.9 m (3 foot), equipped with magnetic propulsion.*[30][31][32]
- *JD.com launched an Urban Smart Logistics Institute in 2018 to study underground logistics systems for their fulfillment centers.*[33] *No details have been published, but animations show a system similar to CargoCap.*[34] *JD.com is reported to be collaborating* with the American firm Magplane Technology Inc. to develop a magnetic levitation *system.*[35]

2.3 The 5th Transport Mode - Capsule Pipelines

The 5th transport mode, pipes, is since long dominating for the transport of water, sewage, heating and gas. Underground pneumatic pipes were used in 44 cities for transport of letters in capsules from 1853 to 2002, but were outcompeted by motor vehicles, and e-mails, and unable to carry the packages that dominate post services today. Today pneumatic transport systems are used within buildings, e.g., most hospitals for samples to labs, banks, and retail for cash, and in government agencies for sensitive documents.

The timeline of the most important capsule-pipe systems is shown in Figure 1.

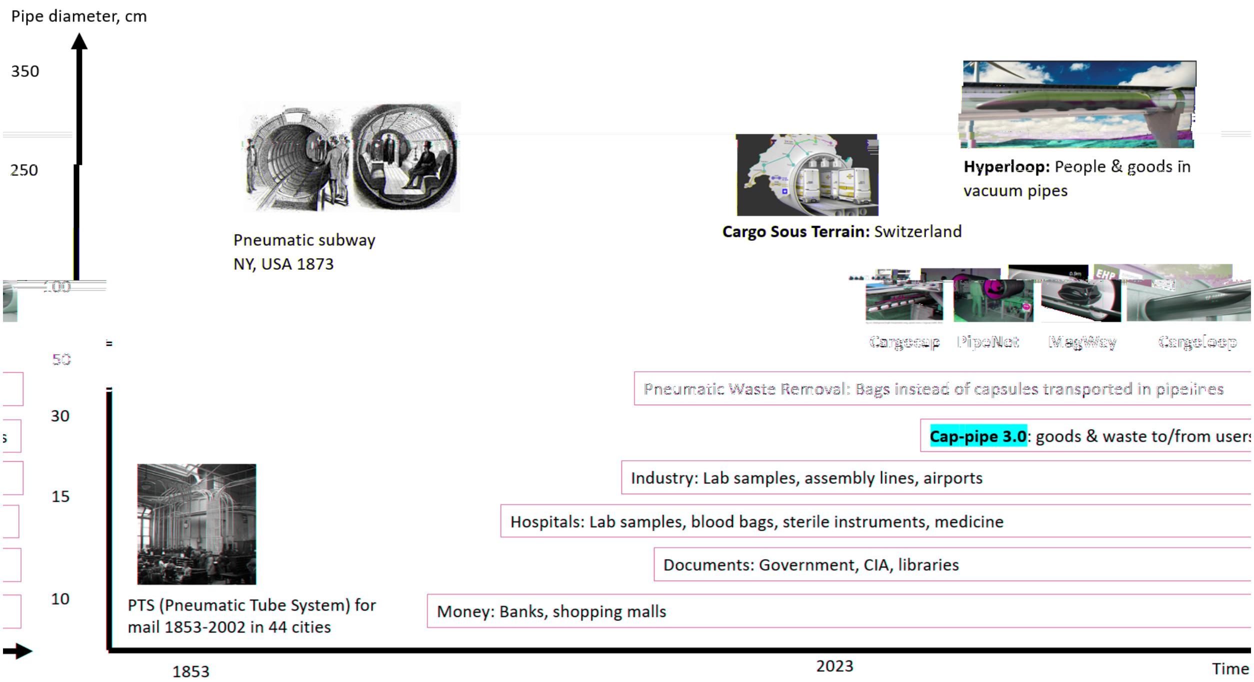

Fig. 1. Capsule-pipeline transport yesterday, today, and tomorrow

We have found four companies developing capsule-pipe system for transport of small items and waste in cities. It is CargoFish 2023, Pipedream Labs 2023, Omniloop 2023, and Tubular Networks 2023. The first two uses electric motors and wheels on the capsules while Omniloop uses a combination of pneumatic and electromagnetism to propel and steer the capsules.

3 Purpose and research questions

The purpose is to explore the addition of the 5th Transport Mode, Capsule Pipelines, to urban logistics by answering the following research questions:

- Is it technically feasible?
- For what will it be used? At home? At work?
- Pain points, risks, and challenges? How can these be mitigated?
- What are the benefits of each service? How much are users willing to pay?
- Is it economically feasible for society? For each stakeholder in the ecosystem?
- How can it enable: Physical Internet? 15-minute City? Circular economy? Retailing?
- Impact on CO2 emissions, environment, and street space?
- Need for further research and development?

4 Design/methodology/approach

An assessment of the state of the art was made based on the analyses of about 3000 articles reporst and patent applications together with participation in some 50 workshops and conferences for five years.

A first basic design was made based on the pneumatic technology used in hospitals and industry as depicted in the central part of Figure 2.

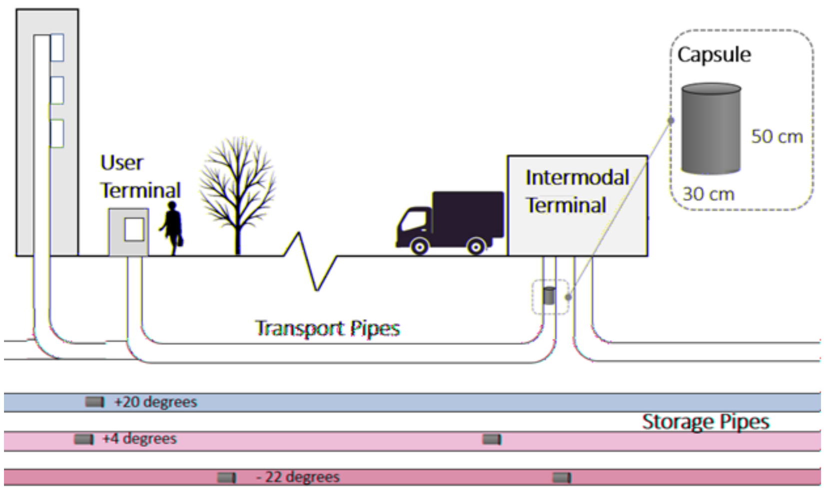

Fig. 2. Basic Urban Capsule-pipe Logistic System

About 40 people were interviewed about using the system in their daily life at home and at work. Based on the requirements from these use cases a second design was made and used in more interviews. We formed the company Omniloop and filed patents that describe the innovations required to provide these service use cases. A LEGO model illustrating some of these use cases was built and displayed at exhibitions, conferences, and workshops.

5 Research Findings

5.1 Potential uses of an urban capsule pipeline

After two years of iterations with some 300 interviews about 30 generic use cases with new technical solutions were developed as illustrated in Figure 3.

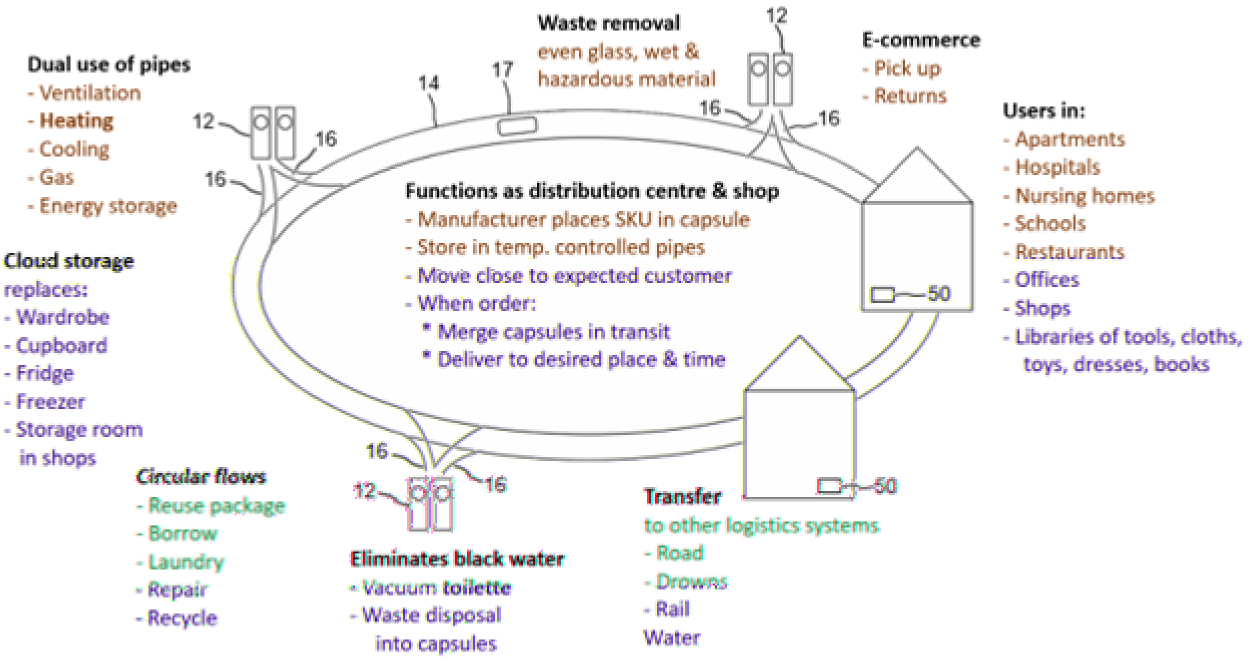

Fig. 3. Examples of services based on the capsule pipe infrastructure

The LEGO model was displayed at a LEGO-exhibition with were 81 filled in our survey. The results of the survey are reported in Wandel et.al. 2022.

5.2 Technical feasibility

From the 30 generic use cases we identified technical requirements. 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.

5.3 Contributions to the concepts:

5.3.1 Physical Internet

Based on the description of the physical internet concept in ALICE 2020 and in Milnkovic 2022 we found:

- The capsule in the capsule pipeline system can be considered as PI container.
- Both the capsules and the infrastructure with pipes, switches, and terminals are shared among all logistics providers

- Since capsules can be moved and parked at low cost the usage of the infrastructure is optimized in real time.
- Cloud/shared warehouses. Goods in capsules are automatically stored in zones with deferent temperatures and automatically retrieved and delivered within minutes. This enables automatic order fulfillment.
- One SKU of a product can be packed in a capsule at place of production, stored in speculation in the pipes, and delivered when the customer orders it. No terminals, warehouses, picking, consolidation, or de-consolidation needed. Even private items as shoes, cloths, tools, toys, wine, and food can be stored in the pipes.
- All shipments to and from a user are consolidated into the same pipes and terminals. Products to users and from users packaging for reuse and waste reduces empty runs
- The system enables marketplaces and circular economy business models
- The integration with other transport means is done with open software
- Physical Interoperability of assets and resources (load units, transshipment, etc). Capsules are automatically transferred to/from load units suitable for other transport means, e.g., boxes for cargo bikes, sidewalk robots, and drowns, pallets or swap bodies for trucks and trains, and containers for sea and air transport
- Synchromodality, (intermodal) routing. Capsule-pipeline can be operated both in sequence with other modes and in parallel to enable load balancing.
- All capsules and components of the system have many sensors and actuators that are connected using Internet of Things protocols, preferably 5G low bitrate
- The capsule is both a unit load, a secondary packaging, and a vehicle

5.3.2 The 15-minute City

- Everyone citizen, shop and establishment have access to a user terminal in the yard outside the front door or in the apartment or workplace.
- Most merchandizes can be shipped with about 5-minutes lead time 24/7
- Products can be sent for services as cleaning and repairing without any person traveling with it

5.3.3 Circular Economy

- Much easier to recycle and reuse packaging and products
- Enabling circular economy concepts such as borrow, share, repair, reuse, and recycle.
- One direct channel between users and providers both up and downstream.

5.3.4 Automatic Stores and Order Fulfillment

- The user can decide when and where to pick up a shipment since it is parked in the pipes close to were the reciever is expected to be.
- Goods can be stored in capsules in pipes in different temperature zones.
- Capsules with items can automatically be stored, sorted, and retrieved
- Thereby replacing some wardrobes, freezers, parcel lockers, micro-fulfillment centers, and even complete retail stores

5.4 Economic Feasibility

Using data from a small town we analyze costs and space saved. We assumed an installation cost of 2 400 EUR per user if 50 persons share one user station. This is twice the cost of a pneumatic waste collection system. To calculate the benefits, we estimated cost savings per type of service from an average person living in the town as shown in Table 1.

Table 1. Economic benefits per user in EURO in one scenario.

Service\Benefit per user	Vehicle km/year	Transport-cost/year	Space saved	Rent for space/year	Cost reduct./year	Pay back years
Waste removal	7	9	0.21	16	25	96.0
Distribution of mail & newspapers	251	359	0.76	60	419	5.7
Bought delivery of merchandises	528	756	1.60	126	882	2.7
Own picking up merchandises	786	658	1.23	87	745	3.2
Total to/from home	1 581	1 782	3.80	289	2 071	1.2
To/from work places (30% of above)	474	535	1.20	87	622	3.9
All above services	2 055	2 317	5.00	376	2 693	0.9

Additional results from the economic analyses were:

- The value of the saved space was 1.6 times larger than the investment cost
- It was profitable to install a user terminal in a kitchen if the investment cost was less than 40 000 EUR

5.5 Reduction of Climate Impact in the scenario

- A 5 kg capsule does, in many cases, the same job automatically as a motor vehicle with 500 times larger mass and a driver.
- 2 055 less vehicle*km/year per user means 30% less traffic parking, emissions of harmful particles and noise
- Emissions of CO_2 were reduced by 760 kg/year and user, which is 30% of per capita CO_2 in Sweden
- Less need for private cars. About 45% of trips by cars are today only for the transport av items and not people

6 Suggested Research and Development

Even though the proposed urban capsule pipeline system seems technically and economically feasible, societies are not yet prepared. We have identified the following remaining research questions:

- Suitable planning, legal, and institutional framework?
- Regulations regarding safety, security, standards, and cerification?
- Actors in the future ecosystem and their business models?
- Integration with other logistics systems? Information system with AI?
- Simulation models to analyze the best mix of last mile transport means for different types of cities as density; mixt of workplaces, residences, commercial areas; green or brownfield; and future technical year?
- Where to start? Inside buildings, e.g., shopping centers and airports? Between courtyards? Between cities and major air- and seaports?
- Where to place terminals? Courtyards, entrance, shop, or kitchen?
- How far upstream the supply chains? City outskirt? Place of production? For the pipes? For using capsules as the secondary packaging?
- Cost-benefit and life cycle cost analyses?
- Drivers, pain points, and barriers for all stakeholders? Strategies for mitigation the barriers?

- Is it cost-effective to invest in infra-culverts underground and multi-shafts in buildings to prepare for future capsule-pipe systems?
- How to design ventilation, heating, and cooling systems using the same pipes as the capsules?

To achieve all this, we suggest to establish a cluster of researchers to answer the questions above, to develop and test prototypes of the components, a demonstrator, and a full-scale pilot, and plan for scale up.

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