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Urban agrifood circularity: exploring consumable and capital micro circular production loops

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Abstract. The circular economy concept is typically applied at scale, especially for high value products and materials. The dominant manufacturing model is for large global factories with research and practice independent of agriculture. This paper challenges the dominant "big is beautiful" ethos and explores how agricultural and industrial production can operate at local, urban scale with wastes circulating for consumable and capital production. The research case is a UK city where food wastes could be used for food production and beverage production waste could be used to produce building materials. The research explores the industrial symbiosis engineering challenge of small-scale waste conversion and the digital challenge of identifying and measuring waste flows for conversion. In considering waste conversions through local, distributed manufacture this paper also tackles the digital challenge of how to source local, small volume material flow data for optimization. Future potential research avenues of micro manufacture as well as digital twins are discussed.

Keywords: circular economy, urban manufacturing, distributed manufacturing, industrial symbiosis, digital.

1 Introduction

Production has become increasingly global [1]. Responding to the sustainability imperative and digitally enabled production advances [2] there is interest in alternative production configurations, including local production. Technological advances could make small scale production efficient and economically feasible [3] using urban space [4]. Manufacturing and agriculture have been organized and optimized separately which misses opportunities for better resource use and lower environmental impact.

Technical production is now removed from urban centers [5] and whilst urban centers are expanding [6] production is remote with residents increasingly detached from their food [7] and product origins. With the growing interest in urban food production, coupled with advances in controlled environment agriculture (CEA) opportunities exist to exploit advances in technology, urban vacancies, and localized wastes.

This paper draws on exploratory and experimental research on the feasibility of local urban circularity. Local here refers to distances of hundreds of meters rather than throughout a town or city. The research considers how agrifood waste flows can be captured using digital technologies then modeled for nutrients to grow more food or create building products to build structures, i.e., create capital. Secondary publicly accessible data or primary data can be modeled to optimize flows and experiments can test the feasibility of those flows.

This paper first presents available knowledge in urban circularity from peer reviewed literature. The knowledge gaps identified lead on to methods to consider the gaps in digital and physical flows. Virtual models and physical prototypes are then described in the models section. The results from these experimental steps are presented and discussed for the advances as well as the emergent challenges. The paper then concludes with the contributions of the research and potential for future work.

2 Literature focus

This review builds on earlier work to explore (1) urban space for productive operations, (2) small-scale manufacturing, potentially in urban settings and (3) circularity, especially hyper local. Starting with keyword searches for these three groups, particular focus was given to whether theories exist for urban operations, whether micro manufacturing has been applied for low value, non-additive operations and how circularity has been used for low value, low volume, local operations.

Urban space is increasingly for residential dwellings and retail with manufacturing on the periphery [5]. Few authors [e.g. 8] consider exploiting it for productive and clean activities rather than further residential development. Locating manufacturing in urban areas [9] holds potential but could be challenging if higher knowledge or skills are required to fulfil requirements [10], if the technology levels are high. Authors [e.g. 11, 12] see opportunities for food production (including controlled environments such as vertical farms) and link this to circularity which is discussed later. Whilst authors see opportunities for the deployment of manufacturing and agriculture in urban areas, there is a dearth of literature to guide design and implementation. This is particularly so as a system rather than specific technology advance.

Geographically distributed production can be located close to local markets [3] with small scale production, potentially mobile, meeting individual requirements rapidly at low cost [13]. Micro-factories, especially modular, can be small, self-sufficient, and enabled by digital technologies [10]. When related to food, producers “need a well-designed network of scalable and modular manufacturing systems in their geographically distributed production sites.” [14]. Authors show the potential for small-scale localized production, however, when considering the implementations, most work considers high-value processes or products, especially additive.

Exploiting urban food waste circularity has potential [11] but lacks literature on the trade-offs between wastes being used for further food production (retained in the food system) or for technical applications, e.g. building products (lost from the food system but offsetting other carbon emissions). Finally, research on short conceptual circularity loops [15] is not matched by research on the physically short circularity loops.

Modular, small-scale, urban operations come with speculation of better sustainability credentials through productive, localized, circular, customized delivery but performance evidence is scant. An opportunity exists to contribute to exploring farm-to-fork agrifood circularity at a local, urban level with manufacturing as a single system.

3 Methods

From the gaps identified, there are three areas of focus: data flows, flows of nutrients from wastes and flows of building materials from wastes. Nutrients from food business operators (FBO) wastes will be considered for supply to a controlled environment agriculture (CEA) vertical container farm for plant growth. Wastes from beer production will be tested for bio resin extraction to make bio board for construction. Here manufacturing is not solely a technical operation but part of an agricultural system which could advance sustainability by transforming the overall system not just optimizing technical manufacture.

Data capture from a combination of real data and simulated data inferred from norms expected from business operations was input into two computational models. As this was testing feasibility, the data accuracy was not a major consideration and assumptions could be tested through sensitivity analysis. One computational (simulation) model considered wastes and product logistics, the other (optimization) model considered how perishable food stocks can be timely stored and used.

For the nutrient extraction from food waste for food production nutrients, quality was more important than cost and delivery. Desk research evaluated quality (both safety and matching nutrient composition to farm requirements). The focus was whether digester output from restaurant food waste aligned with farm requirements and whether safety risks existed. This determined how much of the nutrients available locally could be used locally and what level of external input was still required.

Finally, the building materials from production waste used lab experimentation to synthesize bio board samples. Spent grain can be used for bio resin extraction, so this tested if a particular brewery waste was suitable for bio resin to create bio board.

4 Models

Three areas were investigated for an urban conceptual model using the UK city of York given its diversity of resource flows. The 200m x 200m area had restaurants, bars, hotels, student accommodation, a brewery, and a vertical farm (**Fig. 1**). The farm is in a shipping container constructed entertainment complex, SPARK:York with production and consumption and a density of valuable resource flows close by. Some resource flows could be accessed live, others could be inferred from public waste data or estimated from geospatial mapping.

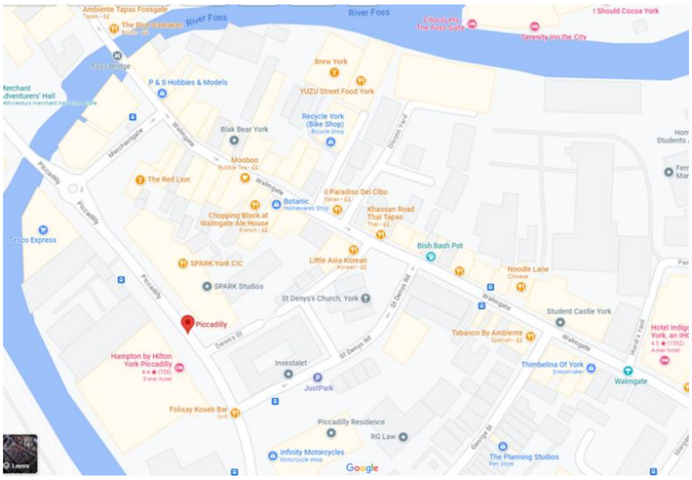

Fig. 1. The Piccadilly area in the center of the city of York (Source: Google Maps).

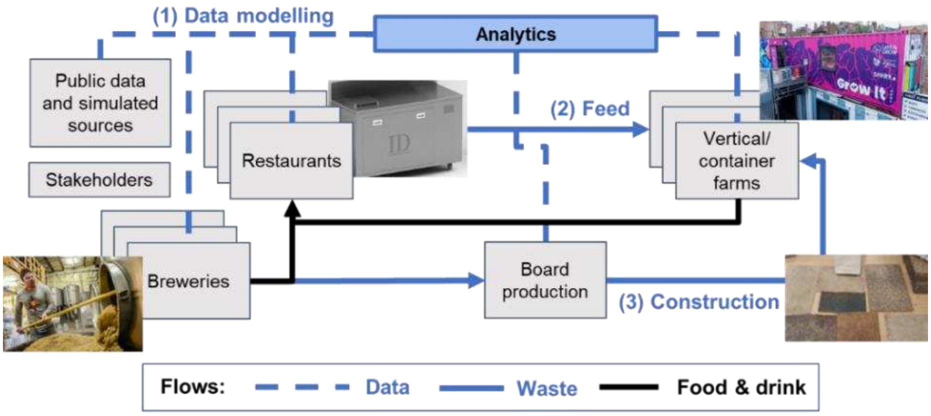

Fig. 2. The urban flows modeled based on the center of the city of York (Source: Authors).

A conceptual model (**Fig. 2**) captured production and consumption, flows of product and ‘waste’ as well as potential data flows. The brewery and container farm supply local businesses with beer and leafy greens (black solid flow lines in **Fig. 2**). Local restaurants could capture their waste foods in an iDigest digester [16] (domestic appliance size) to create nutrients for crop growth (the waste flow “(2) Feed” shown in blue). The brewery could supply its spent grain ‘DDGS’ waste to Wasware [17] to process into materials for creating structures such as a vertical container farm (the waste flow “(3) Construction” shown). Finally, data capture (and estimations) from businesses could feed analytics to improve the system (flow "(1) Data" shown in dashed blue lines). Two models were created to maximize use and value extraction: waste flow logistics between businesses and optimization of perishable food stocks.

5 Results and evaluation

The outcomes for (1) data flows, (2) feed flows and (3) construction flows are reported here. First, data and data flows were captured or created to build two models. Two types of data were utilized: static data for position, capacity, operating hours, etc and dynamic data for demand, production, waste, storage, etc. From this a spreadsheet implementation [18] of material use optimization was chosen for simplicity and flexibility for assessing the storage, use and quality decay for perishable wastes according to customizable profiles. The modeling demonstrated localized flows of waste input, waste utilization and loss of waste due to age. This gave an understanding of potential waste utilization levels. The second logistics model for the system level flows required the complexity handling of AnyLogistix [19]. It incorporated multistage flows from production and consumption including processing to new forms for local use. Given this was to test the concept, previous modeling with live data from the vertical farm through the operating system API was not utilized. The outcome was the concept evaluation of time-based, varying flow volumes through the production assets. Better input data will be needed to evaluate actual performance.

The second area considered nutrients available from IntelliDigest's digestors for safe feedstock for vertical farm crop production. We considered whether nutrients could be used in hydroponic crop production (growth in soil-less substrates). The analysis considered the acceptable minimum and maximum values of plant nutrient requirements for two common CEA target crops (e.g., lettuce, herbs) for a range of macro- and micro- nutrients (ammonia, potassium, sodium, etc) alongside three active vertical farm operations for the same nutrients. Using these target and typical nutrients it is possible to match requirements with the iDigest nutrient outputs. This evaluates how food waste digester outputs (e.g., within restaurants) can be ultimately directed to farms and returned for further crop production.

The third area of investigation was the creation of bio board. These are shown in **Fig. 3**. Spent grain was collected from the York brewery immediately after its use in brewing. This was then processed into bio resin and for bio leather or mixed with chippings, compressed, and cured to produce bio board.

Fig. 3. Brewery spent grain used to create bio resin, bio board and bio leather (Source: Authors)

6 Discussion

The research themes were investigated for their individual and collective feasibility for urban agrifood circularity. This section considers how sustainable manufacturing research can build on this. The following section details future research opportunities.

Firstly, simulation modeling and digital twins are new for urban circularity but not for production or supply chain. Further opportunities arising are how to exploit circular supply chain modeling to evaluate and optimize system performance using public data and data inferred from public mapping. Conceptual feasibility was considered here but not aspects of economic (cost effectiveness), social (employment, engagement) or environment (carbon, best use of agrifood wastes, physical impacts).

The second area investigated was nutrient flows. This drew on historical data and desk evaluation to assess the likely feasibility of using digested food wastes as nutrient feed to minimize the municipal waste collection and reduce import of nutrients, especially by capturing the waste as early as possible before it degrades. Cost and quality need to be compared to current given fertilizer cost and demand for high quality food with increased micro and macro nutrients. Given vertical farm providers optimize nutrient supply for crop and farm operation, the locally processed digestate from iDigest would need to be optimized prior to use in vertical farms..

Lastly for construction waste flows, the research demonstrated several advances. First, spent grain from a local brewery had the necessary composition for multiple material applications. Second, materials could be made to viable quality levels in small scale manual production. Third, the apparent material properties lent themselves to two vertical farm requirements: paneling or shelving. Relating back to earlier, potential local sourcing and local use would ideally be satisfied through local production. Viable production scale is needed. This would be evaluated for its local footprint (physical and environmental). It would be valuable to know if production take place in a permanent or mobile facility.

This research was focused on the feasibility of digital and physical flows. What has not been considered are aspects of efficiency, economics, social impact, environmental evaluation. Scale and efficiency are considered synonymous, however, efficient large systems are not implicitly effective [20]. There is unfinished work here to assess whether sustainable manufacturing would be enhanced through localized, distributed manufacturing. Additionally, no environmental assessments were possible within the scope of work but are needed to understand advantages and disadvantages at system scale and uncover whether there are otherwise hidden negative effects at scale.

7 Conclusion and future research

This paper has considered urban agrifood circularity using a conceptual model of a small UK urban area. The research considered how agrifood waste could be retained and used for value adding production activities at small scale rather than being aggregated and transported away from the city, potentially for low value uses. The research considered three areas: capture and use of data for local flow optimization, processing of food waste into nutrients for the operation of controlled environment agriculture (vertical farming) and processing of waste into bio board for capital infrastructure.

There are contributions to both knowledge and practice. The research outcomes demonstrate feasibility in circulating resources in hyper-local urban settings to minimize transport, exploit high value properties and create opportunities through urban agricultural production, technical production and consumption. There is a 'small is beautiful' challenge to the dominant high efficiency, high volume, regional or global production with significant material, waste, employee and product travel. This learning contributes to directions for sustainable manufacturing research. Contributions from a practice perspective, are on better understanding of how wastes can be used for high value consumables (nutrients for growing food) and capital products (high value building products) that could offset higher carbon material use. This learning challenges the best circularity route for materials and whether flows should be maintained as biological nutrients (renewable) and/or substitute technical nutrient (finite) flows. Opportunities exist for outreach, training and consultancy, to optimize these flows: to educate the public and policy makers to foster understanding for the circular economy, and train and support the participants in optimizing flows. Finally, there are opportunities for discovering new uses of materials to further reduce waste.

There are four areas for potential future research. The first area is modeling. This research used historic and simulated data. There is potential for scaled models using live data. The scale would be presented by at urban area containing multiple business that are for consumption as well as production. Metrics are needed, especially sustainability, to evaluate impacts. Potential extensions are how to cope with very high volume of some data sources and hard to obtain data as well as whether models could progress through levels of sophistication from digital models to digital shadows (live data inputs) to digital twins (live data inputs and decision outputs).

The second area from a manufacturing perspective would be the collection, processing and quality of nutrient flows. Onsite robotic bio-upcycling through the iDigestors onsite enhances the recovery of bio-nutrient from food waste using enzymatic bio-catalysis. Previously work on gem lettuce showed the bio-nutrients are superior in value and balance compared to conventionally sourced nutrients leaving a gap in research for suitable pre-processing for the vertical farm environment.

The third area to investigate is how laboratory material production can be scaled. This is both a general production challenge as well as a challenge to understand if bulky building products can be produced in small scale urban production facilities practically and economically. Additional research would test materials for strength, durability, insulation, etc. hence suitability for construction.

The fourth area for research is evaluation. Here the physical and data flows and analysis were evaluated but not the impact of the new system or the relative impact compared to the current production and consumption system including using urban space and reassigned material. Evaluation of the combined carbon, employment, economic and social impacts to uncover the positive and negative effects of the changes suggested at scale is needed. Cost and impact of circular flow optimization could focus on reducing cost or CO_2e or waste, but these can be time varying and mutually conflicting goals (Reducing waste by refrigeration versus cost by doing nothing).

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