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Article

Metabolism and Urban Design: Insights from the Champs–Elysées, Paris

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Abstract: The urban metabolism concept is crucial for understanding city–environment interactions. Yet, its use in urban design is limited, and the examination of diverse design hypotheses with the potential to influence metabolic activities is seldom undertaken. This research addresses this gap and aims to analyze how the concept of metabolism (1) Can be leveraged by professionals for making urban design hypotheses, and (2) allows for the assessment of each of these hypotheses to reduce adverse environmental impacts and inform urban design decisions. Focusing on Paris' Champs–Elysées redesign, in collaboration with PCA–STREAM, an urban design and architecture firm, this research employs fieldwork observations, tenant/store owner interviews, and specific metabolic models for water, energy, and materials. The results demonstrate that while redesigning the avenue's public space potentially impacts the whole Champs–Elysées metabolism, this impact remains relatively limited. Intervening on objects with higher metabolic activities and using more efficient technologies might be more fruitful in terms of adverse environmental impact reduction, at least in this context.

Keywords: metabolism; urban design; urban development; water; energy; material



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1. Introduction

Since the beginning of the Anthropocene era, world urbanization has placed ever-growing demands on resources and ecosystems [1,2]. In this context, the concept of urban metabolism plays a pivotal role in advancing our understanding of the complex and dynamic interactions between cities and these essential components of the environment [3]. Urban metabolism as an interdisciplinary concept allows for an exploration of how cities use resources and produce waste, as well as the associated societal, economic, and environmental challenges that arise. It also attempts to characterize how cities consume, transform, and reject flows of materials, energy, and water [4]. The more specific idea of the metabolism of the city was mooted by Abel Wolman as early as 1965 [5]. Since then, scholars have been exploring this notion from various perspectives and disciplines [6–8]. Recently, there has been an increasing trend in the examination of urban metabolisms as interconnected and cyclical processes, prioritizing resource efficiency over perceiving them as linear processes [9,10]. Other scholarly work has explored how the concept of metabolism could be coupled with climate studies in order to provide solutions for urban resilience [11,12]. However, this article intends to respond to the call of Bahers et al. [13] by exploring the spatial dimension of urban metabolism. In their literature review, they demonstrated that the notion of space is being directly or indirectly mobilized in several ways by urban metabolism scholars. First, it enlightens the relations of domination between territories [14,15]. Second, it contributes to the exploration of the development of economic activities related to urban metabolism [16]. Third, space is leveraged to analyze the socio-ecological regimes of cities [17–19]. Fourth, it allows for the identification and

tracking of metabolic flows of resources and waste beyond cities [20]. Finally, space is leveraged to understand how urban metabolism can be operationalized and coupled with infrastructure and urban planning and design [21].

The particular concern of this study relates to this last approach, as it focuses on the metabolic contribution of urban design more specifically. It, therefore, explores how designers can re-envision urban design projects that optimize water, energy, and material stocks and flows to diminish adverse effects and impacts on the environment. The notion of urban design is commonly used to encompass anything from the design of a facade of a building to proposals for an entirely new settlement in an urban setting and has been discussed extensively [22]. However, the coupling of urban design with urban metabolism has been a more recent development, as most previous work only focused on the analysis of larger and existing objects such as regions, cities, or neighborhoods that exhibit varying metabolic activities [23,24]. A few serious attempts to move from simple analysis to design have been described by Oswald and Baccini [25], Kennedy et al. [5], and Juwet and Ryckewaert [26]. Oswald and Baccini [25], in particular, provided a framework for designing cities using urban metabolism as a guiding principle. This framework was based on four guiding principles (shapability, sustainability, reconstruction, and responsibility), five criteria of urban quality (identification, diversity, flexibility, degree of self-sufficiency, and resource efficiency), and four major urban activities (to nourish and recover, to clean, to reside and work, and to transport and communicate), as also identified by Baccini and Brunner [4].

Despite these first experiments, the appropriation of urban metabolism by designers remains limited, and the testing of various design hypotheses based on specific design decisions influencing metabolic flows is rarely analyzed [27]. Furthermore, these hypotheses can impact urban spatiotemporal dynamics due to changes in urban morphologies [28] and interconnections between factors related to resource consumption such as population density, building types, or even garden typology [29], which are also rarely investigated.

This research addresses these gaps while conceptually contributing to the debate on the dialogue between the concepts of urban metabolism and urban design. In this article, we hypothesize that this dialogue is happening when professionals are leveraging the notion of metabolism for urban design. This approach advocates the formulation of design hypotheses that deliberately encompass processes associated with the production, consumption, and waste of resources, as well as spatiotemporal dynamics such as changes in urban morphology or uses, for instance. Ultimately, these design hypotheses can lead to a metabolism that holds the potential to mitigate adverse effects and address environmental challenges associated with hyperobjects [30].

Therefore, the aim of this article is twofold:

- (1) To show how the concept of metabolism can be leveraged by professionals for making urban design hypotheses;
- (2) To assess the potential of each of these hypotheses to reduce adverse environmental impacts and inform urban design decisions.

To achieve these goals, we used an iconic urban design project that is currently under development in Paris, France: the re-design of parts of the Champs-Élysées. This ambitious research was realized in collaboration with a French urban design and architecture firm, PCA-STREAM, which led an urban design study for the Champs-Élysées committee and the city of Paris. This research is based on fieldwork observations, interviews with local tenants and store owners, the development of specific metabolic models associated with water, energy, and material flows, and the mobilization of various databases and extensive literature. The results demonstrate that while re-designing the avenue might impact its current metabolism, this impact might not be as significant as envisioned by PCA-STREAM in the first place.

2. Methods

2.1. Context and Design Hypotheses

2.1.1. The Champs–Elysées: History and Contemporary Redevelopment

Described as the “most beautiful avenue in the world” for over a century, the Champs–Elysées Avenue occupies a unique place in the international collective imagination. With 370 years of history behind it, it exudes a uniqueness of place that attracts over 30-million visitors every year. However, since the 1980s, the strong growth of international tourism has changed its profile. Shops gradually took precedence over cinemas, which used to be one of the main features of the Champs–Elysées, and the area attracted more and more offices.

The previous major redevelopment project led by architect Bernard Huet in 1992–1994, which gave more space to pedestrians, did not manage to reverse these dynamics in any lasting way. Today, the avenue is subject to many challenges: intense car traffic, noise, pollution, a lack of green spaces to face the heat island effect due to climate change, and global disaffection and dissatisfaction among Parisian residents in the face of the increasing number of tourists and office workers.

In 2019, the Champs–Elysées Committee, an association founded in 1916 that brings together the various owners of buildings along the avenue, wanted to engage in a fundamental reflection on the future of the Champs–Elysées, which faces a greater than 20% vacancy rate [31]. It commissioned the architecture and urban design agency PCA-STREAM to produce a strategic vision, “Reenchanted the Champs–Elysées,” and an urban design study to make the avenue more “desirable, sustainable, and inclusive” [32]. The perimeter of the urban study mainly includes the Place de l’Etoile, the gardens lining the “lower” avenue, Place de la Concorde, and the “upper” avenue of the Champs–Elysées. It is on this last area that we will focus the analysis of urban metabolism presented here. The calculations consider the road and pavements stretching from Place de l’Etoile to the roundabout, the first 20 m of the streets perpendicular to the avenue, for a total of 70,000 m² of public space, and the buildings in the front line along this area (Figure 1).

2.1.2. Three Design Hypotheses

The urban design study conducted by PCA-STREAM recommends a number of design measures for the “high” Avenue des Champs–Elysées that can impact its metabolism. Leveraging metabolism as a concept to inform urban design is embodied in the firm’s ambition. It is used to drive the firm designs “*toward a symbolic and practical idea of the city as an urban metabolism and pointing toward an approach that takes the ecological challenge into account in order to manage the city*” [33]. However, it is to be noted that, for the Champs–Elysées project, PCA Stream is dealing primarily and almost solely with the physicality of the avenue’s public space. This focus does not extend to encompass the stores and buildings under the purview of the Champs–Elysées Committee. Consequently, this project exhibits a constrained scope, especially when contrasted with the broader range of undertakings typically undertaken by urban designers. With this philosophy in mind, the study contemplated three urban design hypotheses to analyze the influence of design measures on the avenue’s existing and future metabolism:

H1. *Reducing the road to 2 × 2 lanes for motorized traffic (Figure 2).*

This project scenario reduces the number of traffic lanes by one in each direction. According to macroscopic traffic modeling conducted by the mobility consultancy Artelia [34], this scenario results in local and measured traffic shifts, reducing traffic on the avenue by 19% without causing additional congestion. These acceptable relocations of flows on a neighborhood scale are what make the apparent paradox possible, reducing the number of lanes locally reduces traffic locally. From a metabolic perspective, such a reduction might lead to lesser consumption of energy and material due to transportation.

H2. *Increasing green permeable space (Figure 3).*

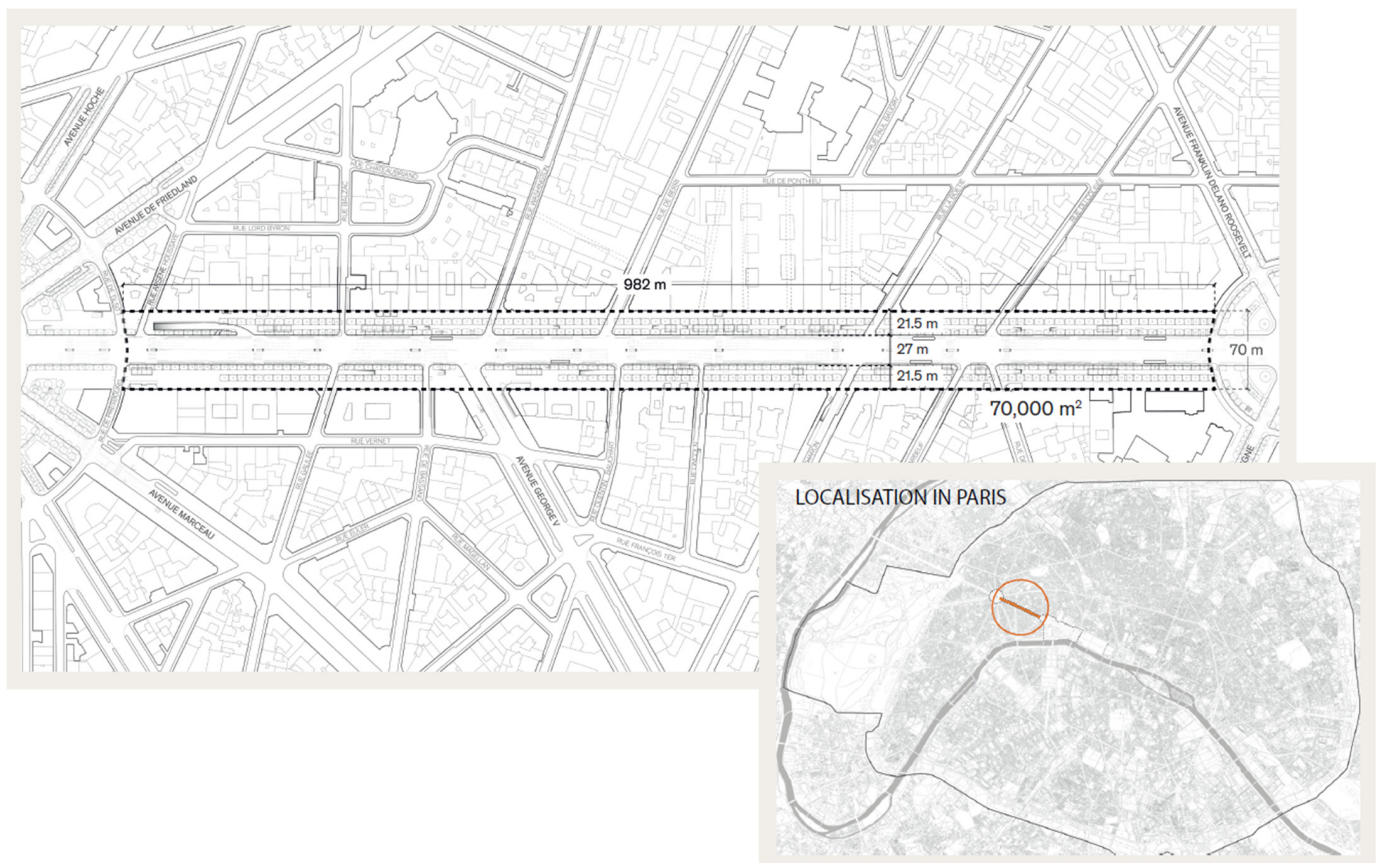


Figure 1. Location and plan of the upper avenue of the Champs-Élysées, dimensions of the public space—PCA-STREAM, 2023.

In the current situation, 98% of the site surface is covered with impermeable pavement [35], mainly granite paving and cobblestones. These impermeable materials do not allow for infiltration, storage, and recycling of rainwater, which flows directly into the sewer system. Furthermore, the tree planting pits present a very limited surface area. For this hypothesis, the volume of these pits is increased and planted with shrubs and ground covers. From a metabolic perspective, and in line with the “Paris Pluie” plan [36], the design also aims to restore the natural water cycle, notably through soil. Stockholm pits are being created for this purpose. These measures lead to a constrained but perceptible increase in permeable floor coverings, as permeable surfaces are multiplied by a factor of 2.3.

H3. Triggering changes in real estate and program uses (Figure 4).

Lastly, the reduction of lanes for traffic leaves more space for bicycle paths and sidewalks. This design approach to provide more space to pedestrians had already been achieved in the former redevelopment of the avenue by Bernard Huet and probably had a lasting impact on the real estate and commercial uses of the avenue. As it was demonstrated in a 10-year longitudinal study following this project [37,38], the avenue has experienced a significant real estate evolution when it comes to specific assets. Therefore, we hypothesize that a similar design approach will contribute to a similar real estate turnover, which in turn will affect the metabolism of the avenue. The selected turnover rates based on the Atelier Parisien d’Urbanisme (APUR) study are presented below in Table 1.

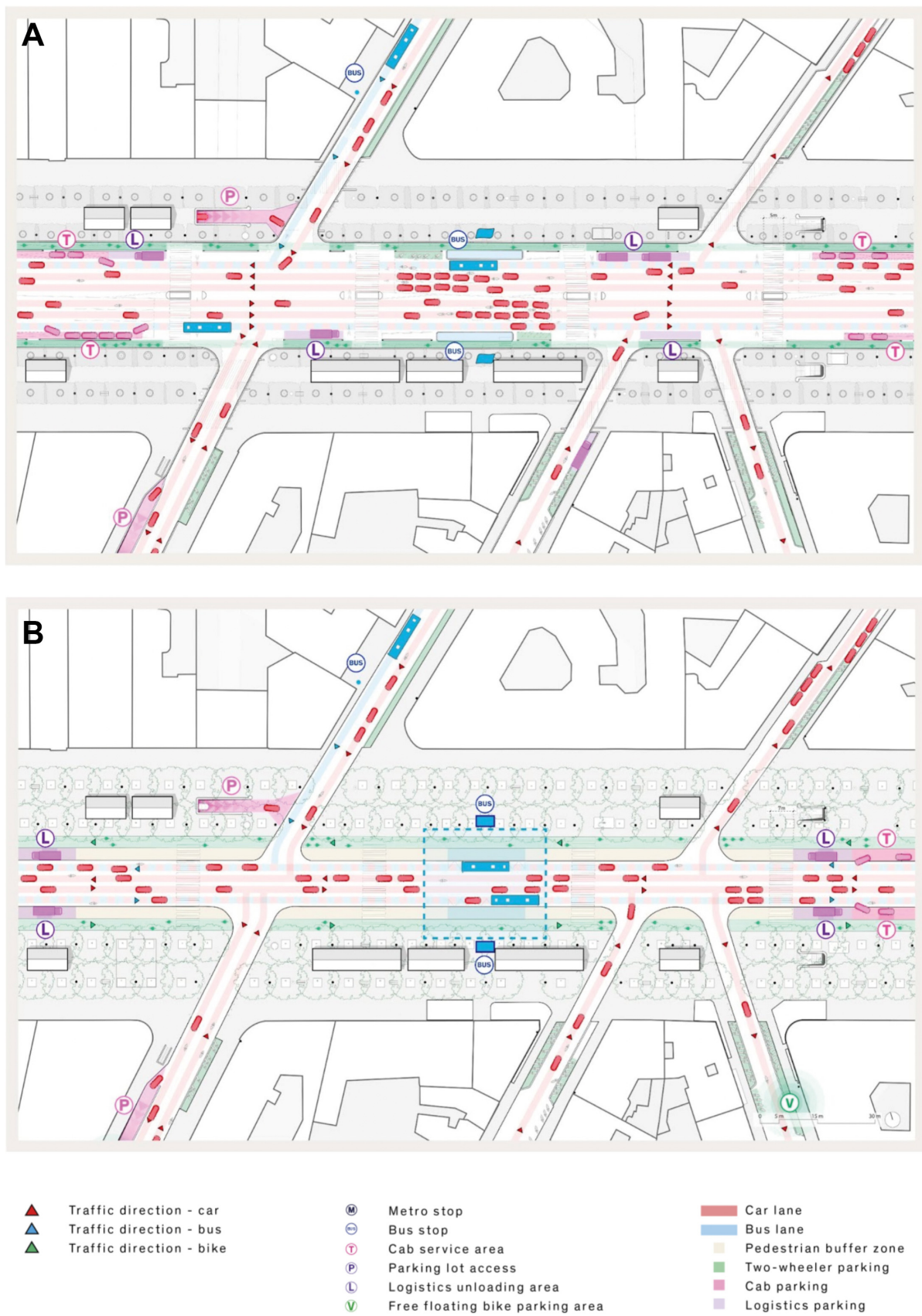


Figure 2. Upper Avenue Mobility Plan (extract); (A) Existing state, PCA-STREAM, 2023; (B) Projected state, PCA-STREAM, 2023.

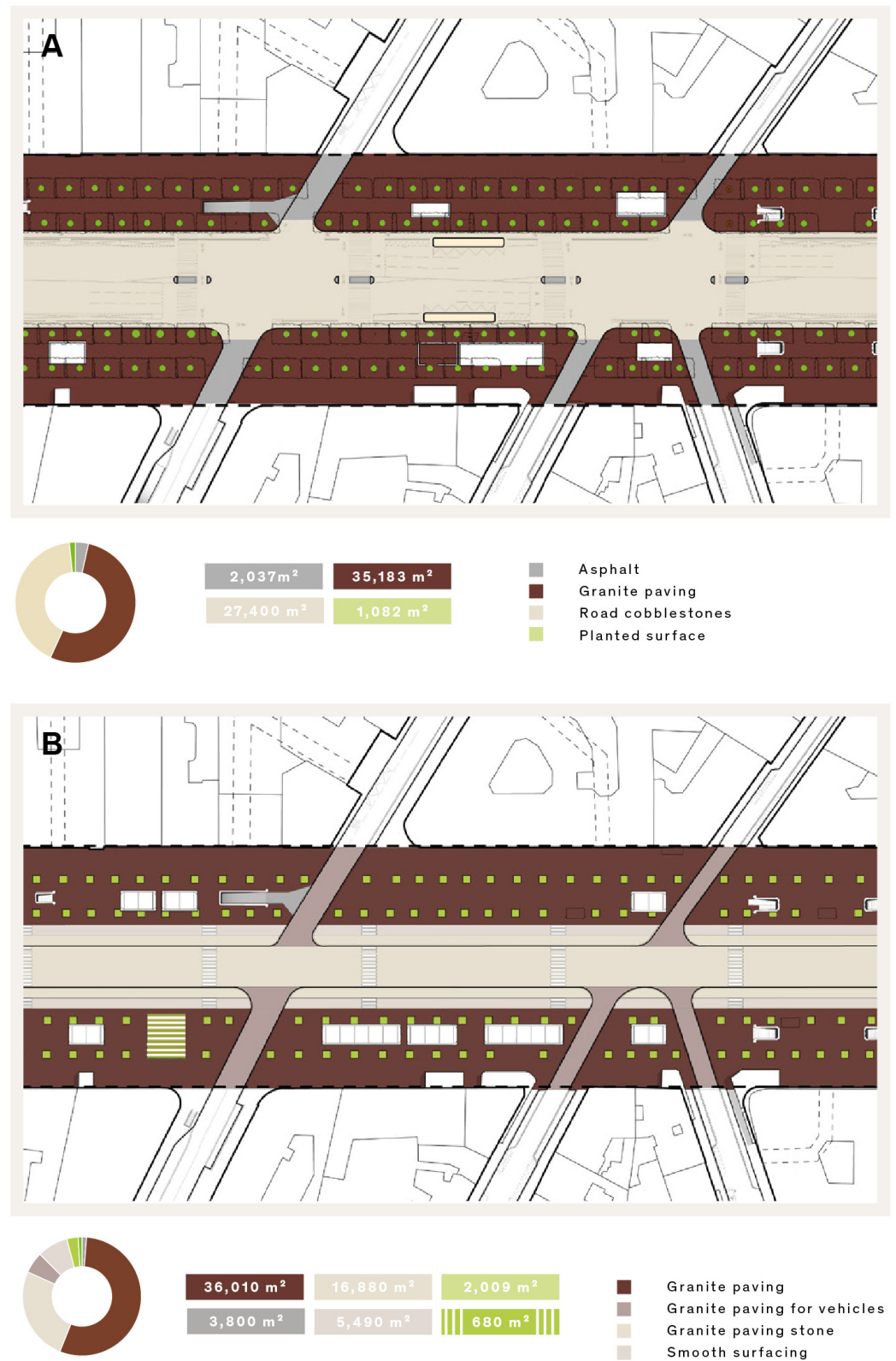


Figure 3. Upper Avenue Plan (extract), typology of floor coverings; (A) Existing state, PCA-STREAM, 2023.; (B) Projected state, PCA-STREAM, 2023.

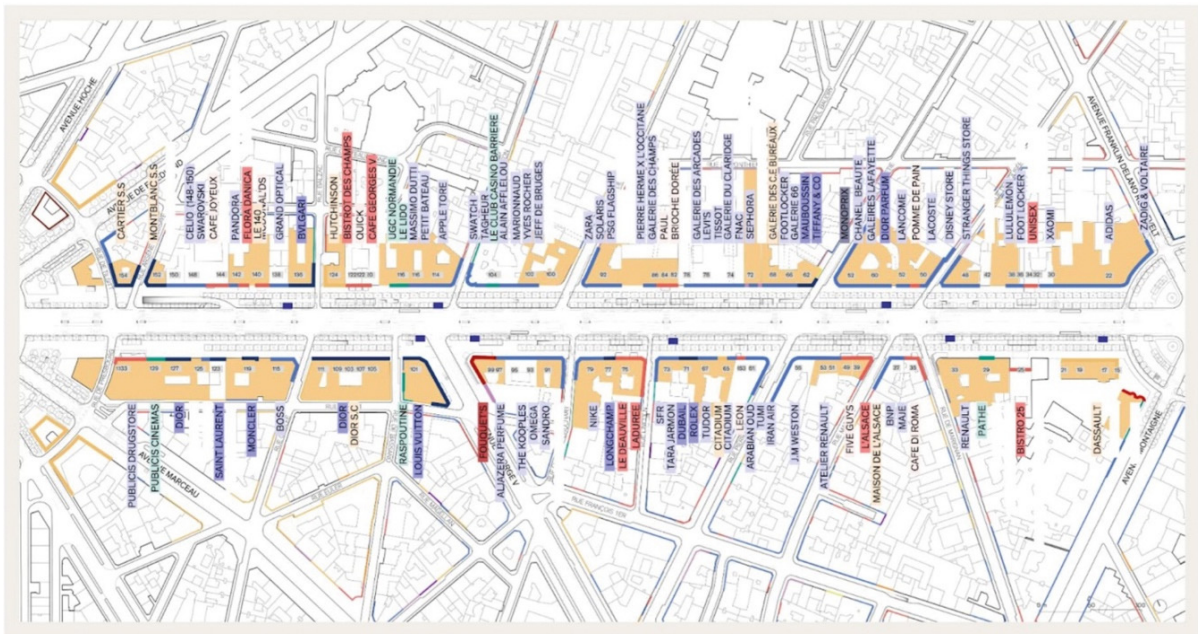


Figure 4. Upper Avenue Plan, an overview of retailers on the avenue in 2023, PCA-STREAM.

Table 1. Selected real estate evolution rates based on the APUR study.

Assets	Real Estate Evolution Rate	Model Hypotheses
Restaurants and food shops/courts	+3%	Addition of one “bistro” restaurant
Retail stores	+1.8%	Addition of: - one luxury goods store - one clothing store
Grocery stores	+1.8%	Extension or restructuring of an existing grocery store
Malls and department stores	+1.8%	Extension or restructuring of an existing mall
Hotels	+5.6%	Extension or moving of one hotel
Offices	+5.6%	Expansion of office space in assets presenting high level of vacancy
Other services	−2.1%	Closing of one movie theater and associated services

2.2. Data Acquisition

2.2.1. Gathering Data

One of the biggest challenges we faced to achieve our metabolic analyses was to find reliable data. This challenge has been formerly expressed by scholars interested in analyzing urban metabolism [15,22]. To get access to data, we deployed several strategies.

First, we relied on data provided by PCA-STREAM, as they could provide precise metrics of the existing avenue and of the redesigned project. These metrics primarily concerned the public space associated with the avenue: surfaces of the sidewalks, bikes, buses, and other motorized traffic lanes, as well as green spaces, terraces, and counter terraces. Data were carefully reviewed and validated by our team.

Second, we collected existing data from variable sources. Data covered at least seven broad categories. They were spatial and population data, construction data, transportation data, information regarding specific stocks of material, and data about waste management and recycling, as well as about water and energy use. The types of sources involved were primarily governmental agencies though also proprietary sources pertinent to particular kinds of materials. While it is impossible here to provide all of the data sources we used, these are compiled in Supplementary Materials and associated Excel models that accompany this article. However, we mostly used data from three main sources:

- The Atelier Parisien d’Urbanisme (APUR), especially their databases on buildings (database “Emprise Bâtie de Paris”) and commerces (database “BD COM”), as well as two of their reports [29,30];
- The City of Paris, especially its databases on bike traffic (database “Comptage vélo”) and motorized traffic (database “Comptage routier”), as well as furniture (database “Mobilier sur voie publique”);
- The Ministry of Ecological Transition national reports on energy and water consumption, as well as transportation.

Efforts were made to use data from the same time frame (2020–2023). However, because such data are not always available, some calculations in our metabolic models were performed with earlier data sets (2012–2020).

Lastly, since some of the current information on the consumption of stores and offices is scarce or nonexistent, we conducted fieldwork observations and interviews with local tenants and store owners. The interviews focused on the commercial activities of the businesses, and, more specifically, on the delivery, stock, and selling of goods they are dealing with. We also asked questions about their electricity and water consumption, often to no avail. We had to refer to other sources since the tenants often do not know about such consumptions. Since not all of the tenants and store owners were available, or wished to respond to our questions, we decided to focus on a sample of businesses that were representative of the avenue and used them as proxies for modeling the metabolic activities of the whole avenue. This sample is presented in Table 2.

Table 2. Sample of stores used to establish commercial activity-related proxies.

	Brand Name	Asset Type	Commercial Activity
1	Bistro 25	Restaurants and food shops/courts	Bistro-type restaurant
2	Five guys		Fast food restaurant
3	Café joyeux		Bakery and assimilated (coffee shop)
4	Celio	Retail stores	Clothes and accessories
5	Cartier		Jewelry and luxury goods
6	Yves Rocher		Cosmetics
7	Pharmacie des Champs Elysées		Pharmacy
8	FNAC		Cultural goods
9	FNAC		Appliances and high tech
10	Renault		Other
11	Monoprix *	Grocery stores	Groceries and diverse consumer products
12	Galleries Lafayette’s *	Mall and department stores	Diverse consumer products
13	Marriott	Hotels	Hotel-related activities
14	BNP **	Offices	Office-related activities
15	BNP **	Other	Bank: Customer service—related activities
16	Gaumont		Movie theater

* As we could not gather precise data during our interviews, we also relied on literature produced by these specific brands for establishing proxies. ** The BNP Bank was located in one building and the ground floor was used for regular customer services, while the upper floors were used by office workers.

2.2.2. Data Quality and Limitations

These three different approaches to gathering data led to different data quality, which constitutes a limitation of our study. Overall, there were three kinds of data collected.

The first is associated with direct and recent field observations and measurements, mostly thanks to the preliminary work of PCA-STREAM. These data are considered to be of the highest quality for the study and concerns, primarily the public space that is being redesigned.

The second is associated with reliable and trusted sources (APUR, City of Paris) that are local and relatively recent (within the 2020–2023 timeframe) while not necessarily being precise. Such sources were mostly used to assess the spaces and consumptions of the commerces located on the avenue, as well as the transportation dynamics at play.

Lastly, some data relied on proxies drawn from wider surrounding areas or scales, as is the case for data extracted from national reports from the Ministry of the Ecological Transition for instance. We also put in that category the proxy data we got from the interviews of our sample of businesses, as well as from less reliable or older sources. This last set of data is what contributes to the limit of our study, as it could bias the results associated with the metabolic analysis of the avenue.

Proportions among each of these three categories were 12% from direct observations, 37% from local and trusted sources, and the remainder involving broader proxies. All data were clearly classified, documented, and replicable. Supplementary Materials and associated Excel models provide more insights into data sources and classification.

2.3. Metabolism: Models and Representational Considerations

2.3.1. Analysis Steps

Our method for analyzing the impact of our design hypotheses was based on two steps.

First, we developed a metabolic model specific to the avenue that we used to analyze, on the one hand, the metabolism of the existing avenue, and, on the other hand, the metabolism of the projected avenue in light of the design hypotheses stated earlier.

Then, we compared the metabolisms of the existing and projected states both mathematically and graphically to determine the extent to which the avenue's redesign can mitigate adverse environmental impacts.

2.3.2. Modeling Metabolism

To create a model of the metabolism of the avenue, we used the mass conservation principle. According to this principle, the mass of inputs in a process equals the mass of outputs, plus a storage term.

$$\sum_p \dot{m}_{input} = \sum_q \dot{m}_{output} + \dot{m}_{storage}$$

m = mass and other equivalent units for energy and water. Time derivatives are denoted by dots.

p and q represent summation over the inputs and output terms

This principle was applied to analyze processes associated with energy, water, and materials stocks and flows in the study. To do so, we built three models using Excel (v.16.77), which adopt a similar structure and accounting technique inspired by material flow analysis (MFA). MFA quantifies the flows of a particular material across various sectors. MFA broadly relies on two main methods: the bottom-up and top-down approaches [39]. The bottom-up method is based on directly collecting flow data from a city or a neighborhood. On the other hand, the top-down method is based on broader input-output data, often at the country scale, that can then be disaggregated at the city or neighborhood scale.

However, in this study, we used a hybrid method to quantify the flows and stock of water, energy, and materials. Hybrid approaches have more recently facilitated the development of methods adapted to more complex metabolic analyses [39]. Consequently, from the bottom-up, we individually investigated the stocks and flows related to:

- (1) The commercial activities associated with the buildings;
- (2) The public spaces (green and otherwise) associated with the avenue as an infrastructure;
- (3) Transportation associated with the flow of various vehicles (bikes, cars, vans, trucks, and buses).

We also used a top-down approach when data could only be collected at the regional or national scale. For estimating material stocks, we also used hybrid dynamic stock assessment models, which depend on the service life of built-up stock and stock renewal rates [40]. These were estimated for stock building artifacts such as the buildings surrounding the avenue, and the road network, as well as vehicles and other specific goods.

2.3.3. Representing and Comparing Metabolism

The final results are represented graphically with Sankey diagrams, named for the Irish Captain Sankey (1853–1926), a mechanical engineer and soldier who used the diagram technique to show the efficiency of the steam engine in 1898. Flow depictions of data generally are grouped often under alluvial diagrams named for their apparent graphic similarity to alluvial flows of soil deposition. The primary difference, though, is that Sankey diagrams show explicitly how quantities of specific elements flow from one state to another. On the Sankey diagram, the width of each flow is proportional to the quantity represented. The proprietary software SankeyMATIC (v.2022) allows for relatively easy plotting of Sankey diagrams. SankeyMATIC (v.2022) provides fit our life-cycle metabolism models best, as they visualize the complex processes from source materials (input) to end-use consumption types (useful output), and finally to outcomes (waste management) through comprehensible one-directional flows. Sankey diagrams are also useful in terms of helping us identify the most significant/insignificant parts in different stages, as well as how the proportions change between stages. Earlier versions of flow diagrams, similar to Sankey diagrams, were devised by Charles Joseph Minard, a French engineer, in 1869 [41].

While we adopted Sankey diagrams to initially represent the flow of water, energy, and materials, we also made stacked bar graphs with percentages deriving from these Sankey diagrams through Tableau (v2023.1), a data visualization software. The stacked bar graphs are used to show percentages of the contribution of different sectors in various stages. The sum of percentages in one bar adds up to 100%. It is worth noting that for the “end-use consumption” part, the percentages of different sectors only represent the proportion of each sector out of the total amount of end-use consumption, not the total amount of inputs or outputs.

Through these two modes of representation, we could eventually compare the metabolism of the existing avenue and its projected states associated with our three design hypotheses visually and mathematically. We compared the production, consumption, and waste of resources both in relative and absolute terms to assess to which extent the redesign of the avenue could reduce adverse environmental effects.

3. Results

3.1. Water

3.1.1. Existing Condition

The results of the water analysis for the existing avenue are presented in the Sankey diagram depicted in Figure 5 and the stacked bar diagram in Figure 6A. They demonstrate that most of the water is consumed by the commercial activities associated with the buildings surrounding the avenue. Of these, restaurants and offices are the biggest consumers (25.9% and 44.8%, respectively) for different reasons. Restaurants consume nearly $14.5 \text{ m}^3/\text{m}^2/\text{y}$ of water, whereas offices consume $1.46 \text{ m}^3/\text{m}^2/\text{y}$. Despite the higher consumption, restaurants occupy a smaller floor surface area in comparison to offices, with $13,000 \text{ m}^2$ and $223,392 \text{ m}^2$, respectively.

The stock and flows of water associated with public space are negligible, as the processes related to evaporation, infiltration, and runoff for the avenue only represent 6.5%. Of these, 3.5% of the water is transferred to sewage.

An important amount of water is associated with leaks, which represents 20% of all the water that is being treated and produced for consumption in France. This high number is probably due to the aging infrastructure and buildings, as it is estimated that 80% of water pipes were implemented before 1990, 31% of which before 1960 [42].

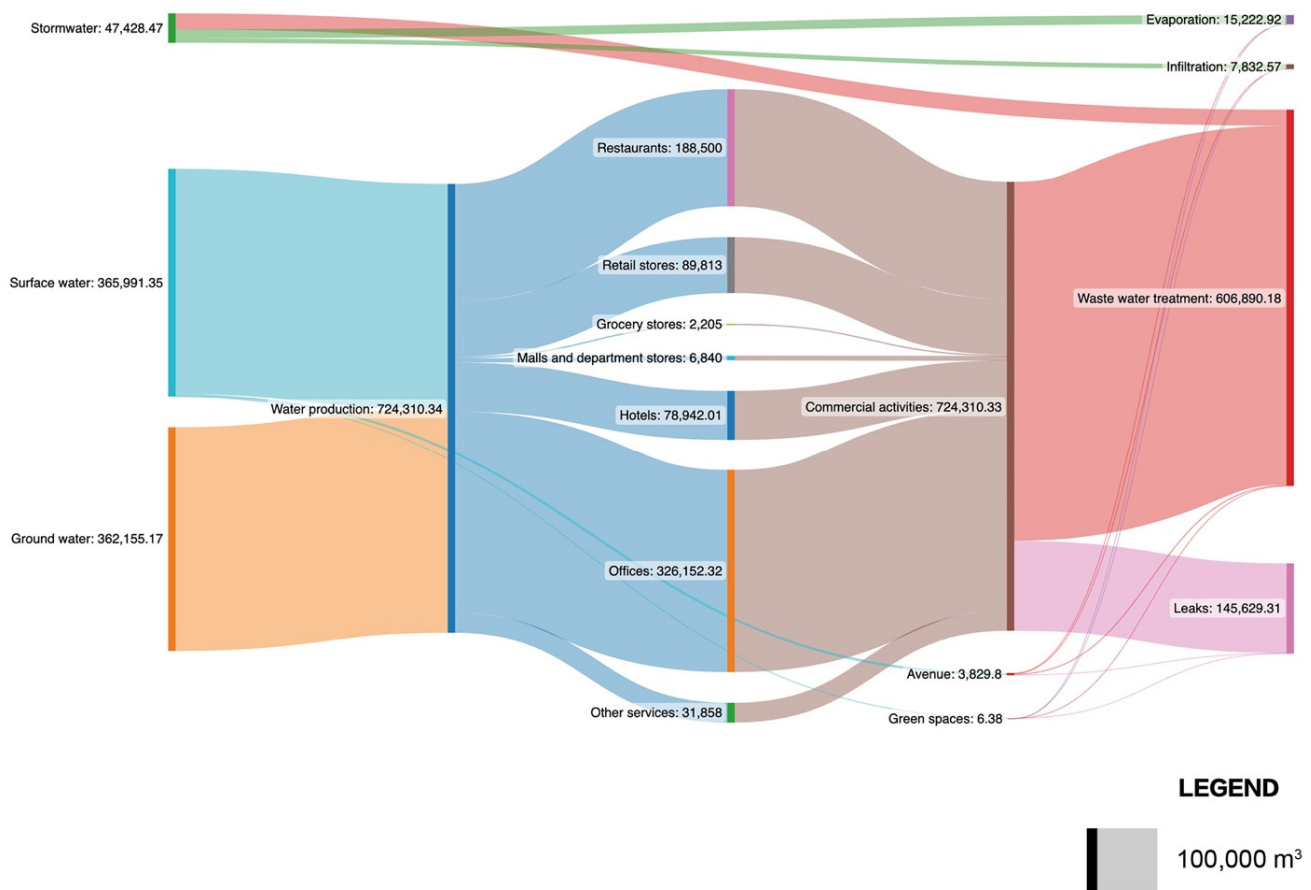


Figure 5. Sankey diagram representing the metabolic profile of the avenue associated with water.

3.1.2. Design Hypotheses

Two design hypotheses potentially have an impact on the water processes at play on the avenue: H2, as it increases the area of green permeable surfaces, and H3 as the turnover of commercial activities leads to changes in water consumption.

The impact of H2 is minimal on the metabolism of the avenue (Figure 6B). The amount of stormwater that flows on the Champs–Elysées remains the same, while the increase of greenspaces contributes to the infiltration of more water on the ground (+345 m³/y), and to more evaporation (+10 m³/y) while decreasing the amount of water that ends in the sewage system (−442 m³/y). However, upon the exclusive examination of the processes related to evaporation, infiltration, and runoff for the avenue, their proportion remains consistent with that of the existing condition, 6.5%.

H3 seems to have a more important impact (Figure 6C). The real estate turnover favored activities that potentially consume more water, such as restaurants, and replace vacant surfaces, which did not contribute previously to water consumption, with specific commercial uses. Therefore, the change of uses contributes to an increase in drinking water consumption (+ 22,668 m³/y), mostly due to the expansion of offices (+18,265 m³).

This is why when looking at the combination of hypotheses and associated diagrams (Figure 6D), the proportions remain the same in the end: 6.5% of the stormwater is evaporated, infiltrated, and goes to the sewage, and 78% of all water is treated, with the remainder being lost through leaks. While less stormwater ends up in the sewage system and eventually goes through wastewater treatment thanks to the redesign of the avenue, more gray water due to increased commercial activities ends up being treated as well.

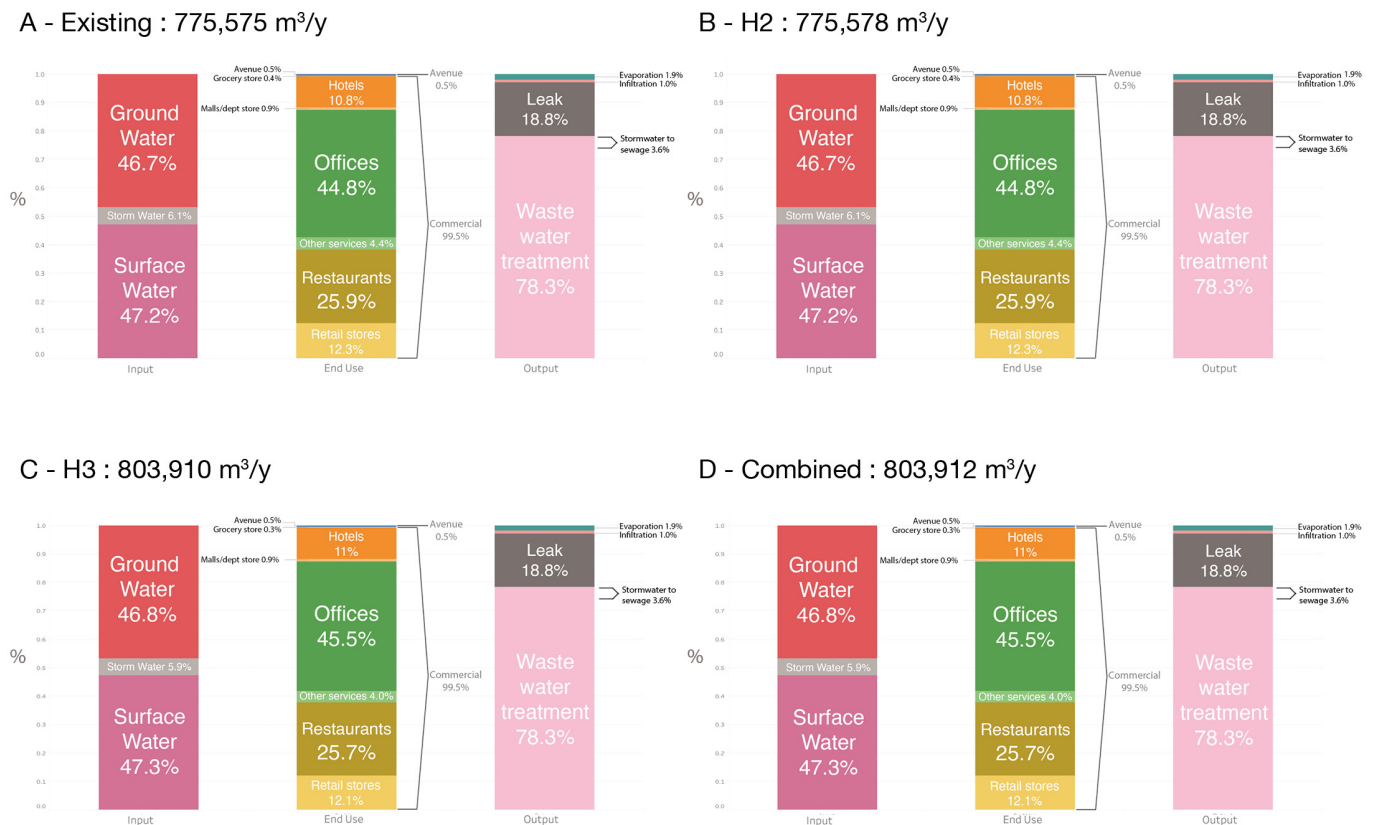


Figure 6. Percentages of the contribution of different sectors associated with water production, consumption, and waste for (A) Existing condition, (B) H2, (C) H3, and (D) Combined.

3.2. Energy

3.2.1. Existing Condition

The results of the energy analysis for the existing avenue are presented in the Sankey diagram depicted in Figure 7. As for the water model, most of the energy is consumed by commercial activities in the form of electricity (Figure 8A). Office space is still one of the main energy consumers (24.6% of all end uses) because of its prevalence in terms of floor surface. However, retail stores and other commercial activities, which include movie theaters and associated services, also consume an important amount of energy (31.5% and 27.1% of all end-use consumption, respectively) despite smaller floor surfaces.

Transportation only represents 3.5% of all end-use consumption and relies mostly on petroleum consumed by private cars, and on natural gas consumed by buses to a lesser extent. Over the year 2021, the city of Paris accounted for nearly 6.34-million cars transiting through the Champs–Elysées. Vans and trucks represented nearly 1-million vehicles.

The energy consumption associated with public space, and electrical urban furniture specifically, is again negligible as it only represents 0.4% of all energy consumption despite the famous and traditional Christmas lights annual consumption (13,176 kWh in 2022).

Finally, 60.2% of the energy in our model is lost, mostly due to electricity production associated with nuclear power generation, as the yield of an average French nuclear power plant is around 32.7% [43].

3.2.2. Design Hypotheses

Here again, two design hypotheses potentially have an impact on the water processes at play on the avenue: H1, as it decreases the number of vehicles transiting through the avenue, and H3, as the turnover of commercial activities leads to changes in energy consumption. It is to be noted that the energy consumption of the avenue itself due to urban furniture did not change between the existing condition and the design hypotheses.

This implies that the energy consumption of the avenue remains negligible again compared to those due to transportation and commercial activities.

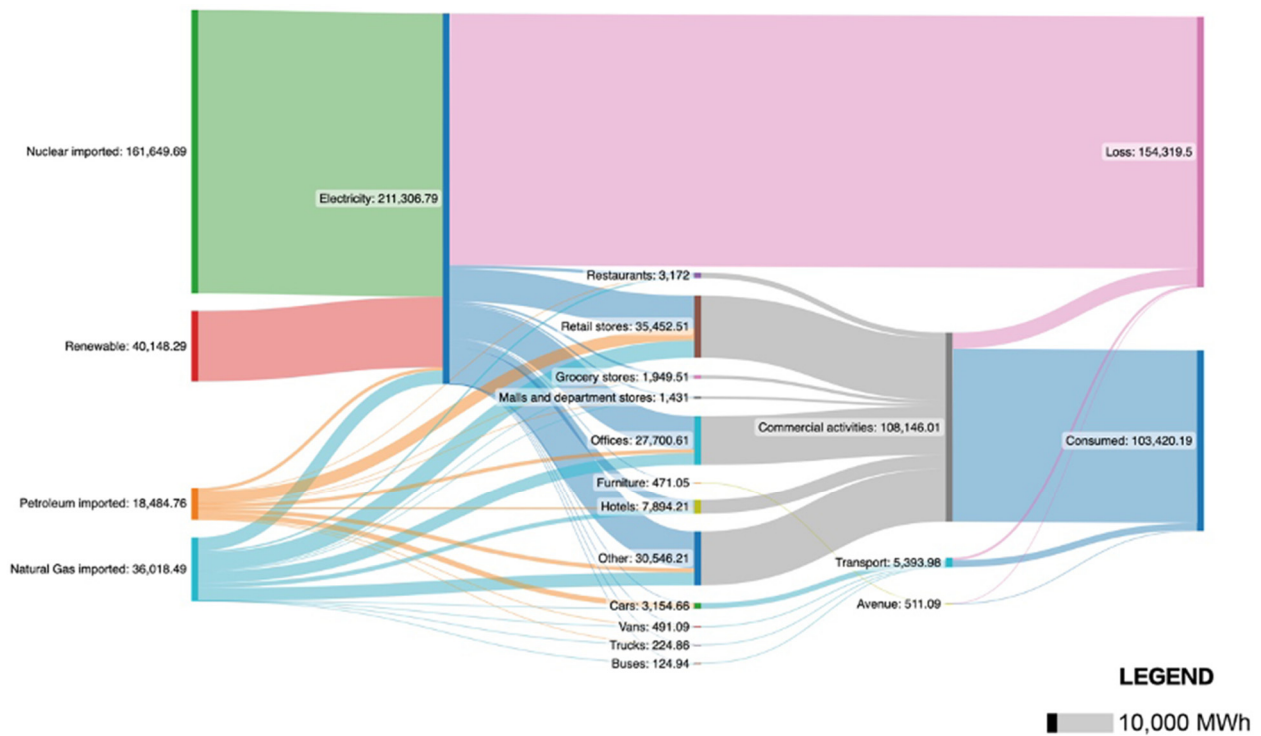


Figure 7. Sankey diagram representing the metabolic profile of the avenue associated with energy.

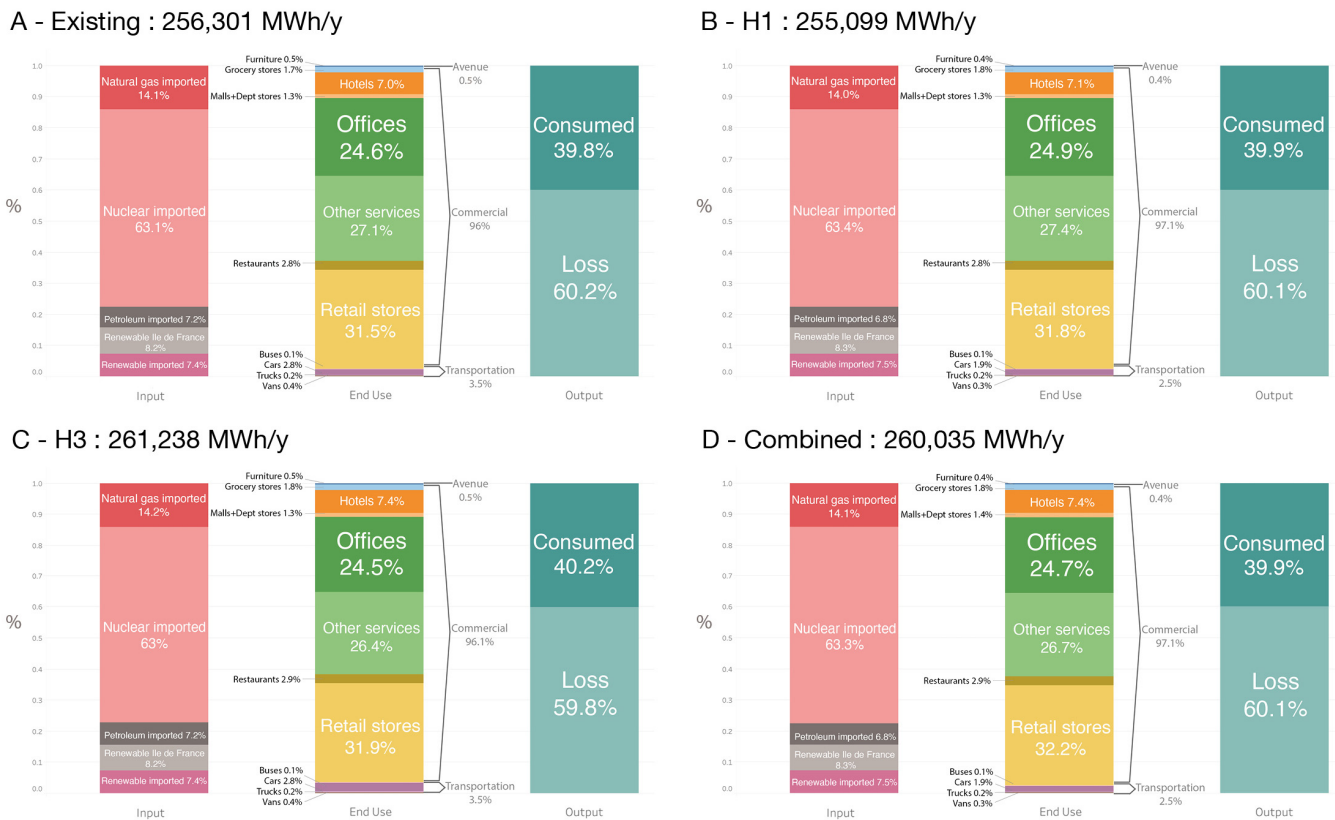


Figure 8. Percentages of the contribution of different sectors associated with energy production, consumption, and waste for (A) Existing condition, (B) H1, (C) H3, and (D) Combined.

The impact of H1 on transportation energy consumption alone is significant, as we can observe a 30.7% decrease in energy consumption associated with the 19% reduction in the number of vehicles, mostly cars, and then trucks and vans that are not delivering goods on the avenue. However, this decrease remains negligible when integrated into the bigger picture that considers commercial activities. While transportation represented 3.5% of all end-use consumption for the existing condition, this number reached 2.5% when H1 was implemented (Figure 8B).

The impact of H3 on the Champs–Elysées metabolism is a bit more significant in absolute terms but relatively negligible when looking at changes in energy proportions between the existing condition and the redesign of the avenue (Figure 8C). The increase of commercial activities due to the real estate turnover leads to an important increase of energy consumption (+4936.5 MWh/y). However, this increase only represents 1.9% of all of the energy considered in the model that is being used from transportation consumptions, especially when looking at the metabolism due to the combination of both hypotheses.

Similar to the water model, the reduction of consumption due to transportation on the one hand is compensated by an increase of consumption due to the increase of commercial activities on the other hand.

3.3. Materials

3.3.1. Existing Condition

The most complex depiction of the Champs–Elysées metabolism is associated with materials production, consumption, and waste processes. As depicted in Figure 9, most of the material flows and stocks translate the two main activities of the Champs–Elysées: shopping and transportation. Nearly 95% of all materials are only transiting through the avenue and are effectively consumed and/or wasted off-site.

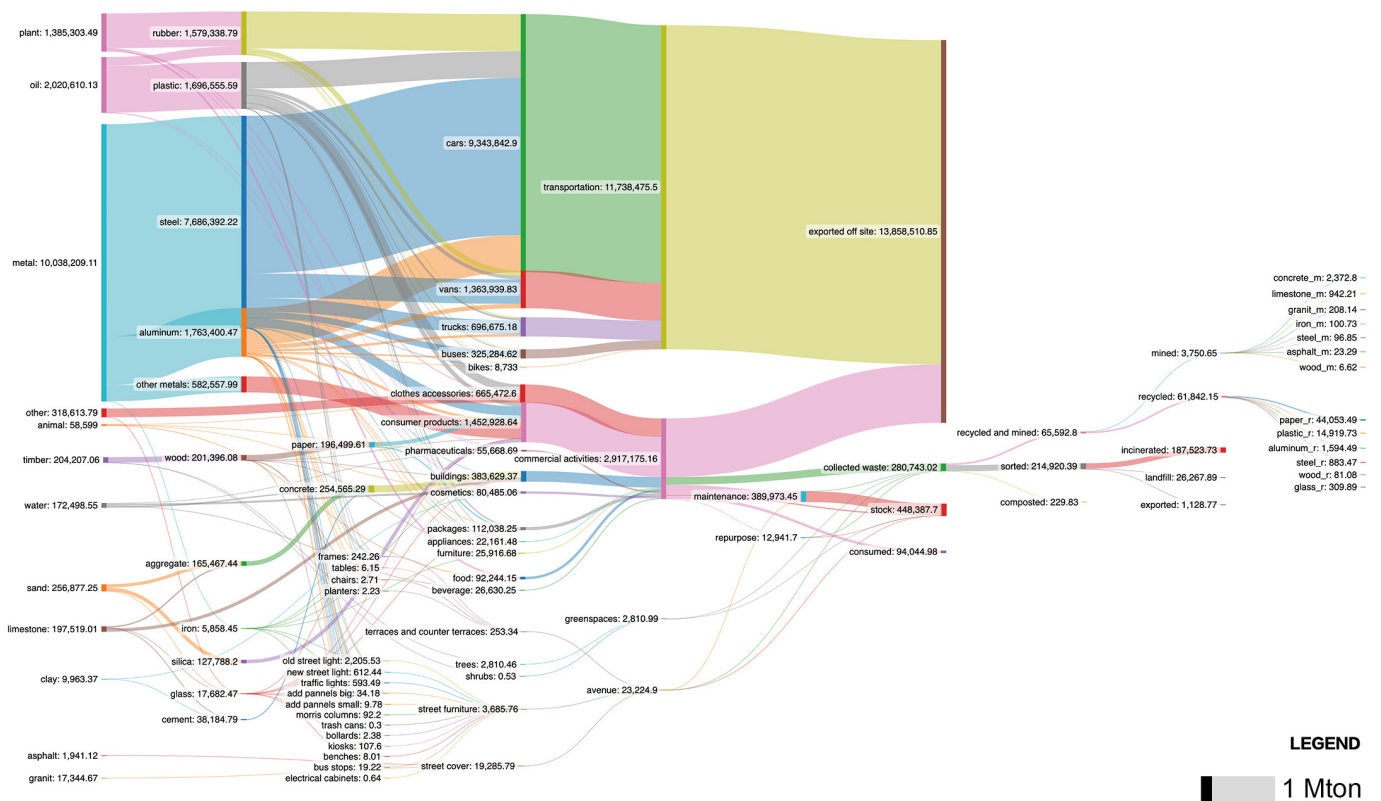


Figure 9. Sankey diagram representing the metabolic profile of the avenue associated with materials.

Of these 95% of materials, 80% are due to transportation. This perfectly transcribed the fact that the Champs–Elysées remains one of the main Parisian highways, and that

most of the materials that transit through the avenue are associated with metal in the form of steel and aluminum. Metal is ubiquitous in our model, as it is also used for other goods that are exported off-site (such as high-tech goods, some consumer goods, and jewelry among others) or used on-site (for buildings appliances and street furniture for instance). Furthermore, the density of metals is high (steel = 7860 kg/m³, aluminum = 2710 kg/m³), which explains the huge imbalance compared to other materials such as plastic, which is also ubiquitous but less dense (the density of high-density polyethylene is only 940 kg/m³, for instance).

The on-site consumption due to commercial activities is mostly associated with offices, movie theaters, some local services, and restaurants, but only represents 19.9% of the stock and flows of materials.

We can also observe that the stock associated with the buildings and the road infrastructure remains negligible at the scale of all of the materials that are transiting through the Champs–Elysées over a year. While Haussmaniann buildings, which constitute most of the building stock, can be pretty heavy, they “only” represent 3% of the total weight of materials. The weight associated with the avenue’s granite paving and cobblestones, asphalt cover, and mostly steel and iron furniture is abysmal as it only accounts for 0.2% of all the materials considered in our model.

Therefore, the amount of waste associated with the ongoing activities happening on the avenue, while important (nearly 281,000 tons per year), represents less than 1.9% of all of the materials that are being processed, of which 23% are either mined or recycled.

3.3.2. Design Hypotheses

All three design hypotheses were considered for the material model (Figure 10).

H1 is the one that induced the most drastic change in terms of material consumption. The reduction of the number of vehicles due to the restructuring of the avenue led to a global decrease of 3.5-million tons of materials per year transiting through the Champs, most of which are metal. Consequently, while in the existing condition, 80% of consumed materials were associated with transportation, this number reaches 73.5% under the conditions of H1. Therefore, H1 induced an increase in metabolic activities due to commercial endeavors in relative terms (+7%), even without accounting for the real estate turnover.

When looking exclusively at the impact of the real estate turnover induced by the redesign of the avenue (H3), we can observe that this increase only represents 1%, while the proportion of materials due to transportation remains high (79%). Therefore, H1 has more impact on the metabolism of the Champs–Elysées than H3.

The combination of both hypotheses (H1 and H3) does not drastically change the proportions of consumed materials due to commercial activities (26.4%) and transportation (73.3%) compared to the figures obtained by implementing H1. This combination also leads to a slight increase in material consumption compared to the implementation of H1 alone (+45,450 t/y) due to the increase in commercial activities induced by real estate turnover. It is also to be noted that the real estate turnover contributed to an increase in the amount of waste due to the refurbishing and repurposing of shops and office space (production of 6000 t/y under the combined scenario), but this figure remains negligible compared to the amount of waste generated by other commercial activities and associated on-site consumptions (289,000 t/y).

Lastly, the impact of H2 is negligible. While the increase of permeable surface and canopy coverage led to an increase of 284 t/y of material related to green features (Stockholm pits, trees, and shrubs), this represents less than 0.1% of all material-related stocks and flows on the Champs–Elysées.

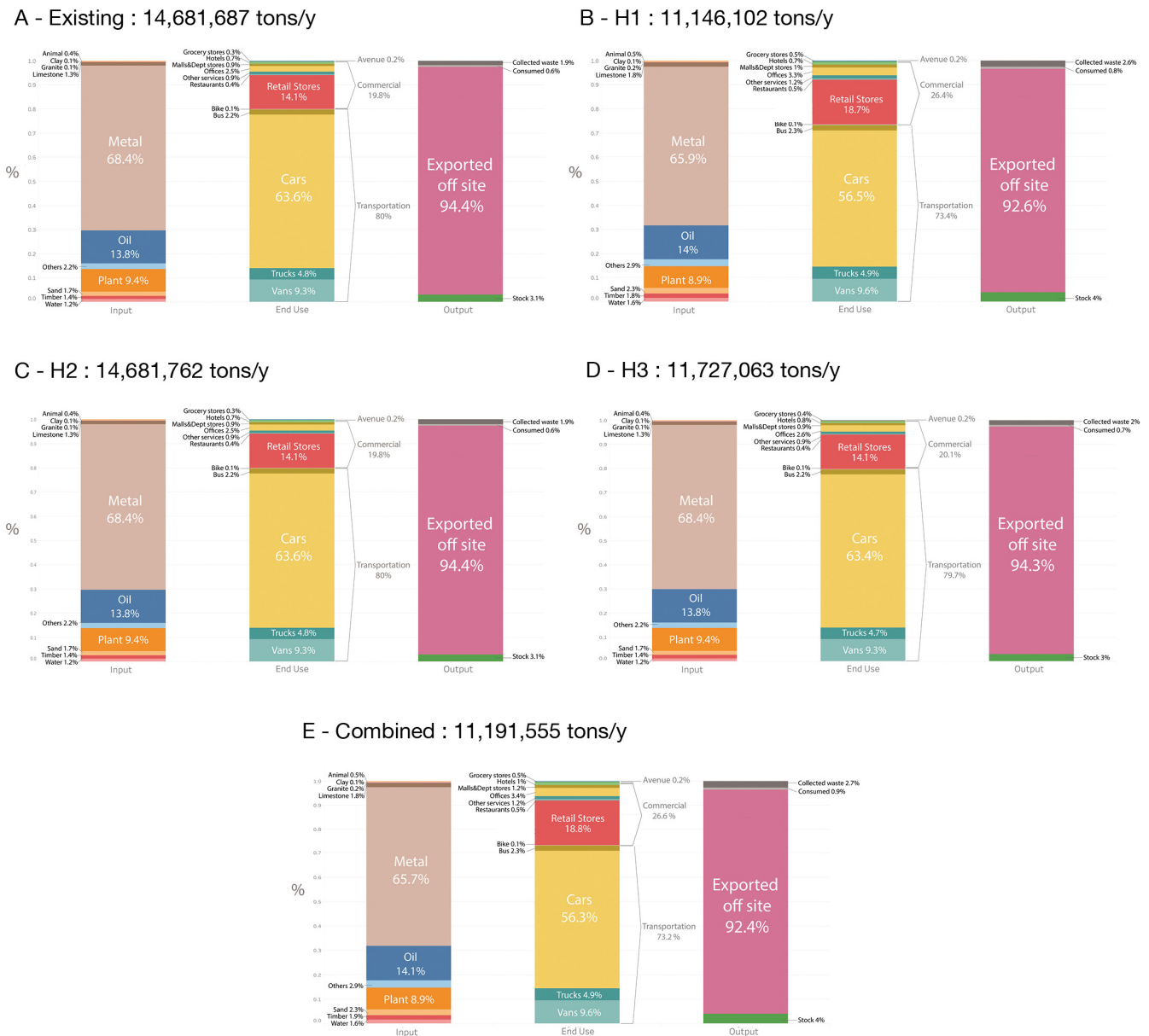


Figure 10. Percentages of the contribution of different sectors associated with materials production, consumption, and waste for (A) Existing condition, (B) H1, (C) H2, (D) H3, and (E) Combined.

4. Discussion

4.1. Assessing the Metabolism of Urban Design

The concept of metabolism originally draws an analogy to the functioning of a body, with the city representing the body. In this context, the Champs–Elysées can be envisioned as a substantial artery, while the stores can be likened to various organs consuming water, energy, and materials brought to them through this artery. Building on this metaphor, we can assume that the metabolic activity of the artery itself is less important in terms of water, energy, and materials consumed than that of the organs. Indeed, we can observe discrepancies in metabolism activity between the Champs’ public open spaces and its buildings accommodating stores, hotels, movie theaters, and offices. The main road and sidewalks exhibit a low metabolism, regardless of the model we used (water, energy, or material), with proportions of associated consumption ranging from less than 0.1% (for materials) to 6.5% (for water) compared to other activities.

Despite the avenue’s low metabolism, its design can have low-to-high metabolic impacts on other “organs,” depending on the hypotheses considered.

For instance, the H1 design hypothesis has a high metabolic impact. Reducing the number of lanes leads to less traffic and transportation-related impacts, especially when looking at material flows. However, it could also potentially adversely affect logistics flows and deliveries, especially when considering the increase in commercial activities due to H3. It also implies a shift of traffic to other routes that was not assessed by our models. This, therefore, highlights the importance of scales and study perimeters when assessing metabolic activities.

However, the H2 design hypothesis has a low metabolic impact. Certain changes, like alterations to soil permeability due to specific materials and planting, only result in small alterations in the quantity of water and materials that were produced, consumed, and wasted, compared to other factors accounted for in the models, such as commercial activities change due to the real estate turnover.

Ultimately, the redesign of the avenue, aimed at reducing environmental impacts, might not achieve its objectives, or at least partially. This redesign will most probably lead to an increase in water and energy consumption due to an increased real estate turnover, aligned with the objectives of the Comité des Champs, which aims to dynamize the avenue's commercial activities while reducing vacancy. However, these increases are not so desirable from an environmental standpoint for either PCA-STREAM or the city of Paris, which aim to reduce resource consumption generally. Furthermore, this analysis highlights that there are still concerns to address. For materials, there may be a reduction in vehicle emissions, but important questions arise about the displacement of trucks and vans for instance.

4.2. Implication of Metabolism Studies for Urban Design

However, our study demonstrates how design can be leveraged to assess the avenue's spatiotemporal dynamics associated with its metabolism. Triggering changes in the urban form and structure of the avenue can have effects of various amplitudes in terms of metabolic impacts. This is mostly due to the change of human activities triggered by real estate evolutions associated with the redesign of the avenue. This raises significant questions regarding the role of design in contributing to resource conservation rather than exacerbating resource depletion and climate change. In the case of the Champs-Élysées, the redesign appears to lead to increased resource consumption and not less.

When presented to the design teams at PCA Stream, these results proved somewhat disheartening to their reflections on the role of urban designers. They also show that dealing almost solely with the physicality of the avenue's public space constitutes a limited urban design approach. This highlights the limitations of soft techniques, like design, in comparison to hard techniques involving technological interventions to improve the metabolism of an urban design project. Enhancing the avenue's metabolism would entail investments in technologies that reduce water and energy consumption, optimizing infrastructure to minimize leaks, and exploring more efficient energy generation technologies to mitigate energy losses. However, addressing material consumption is more challenging as the primary purpose of the Champs-Élysées remains centered around shopping, mostly attracting tourists coming from all over the world, inducing significant waste management issues. The complexity of behavioral changes required to reduce consumption suggests that simply redesigning the avenue may not be sufficient. Design alone cannot solve the world's challenges when it comes to resource depletion and ecosystemic losses.

However, this does not imply that we should cease designing such spaces. Urban design encompasses more than the quantitative accounting of water, energy, and materials. It also encompasses the quality and livability of spaces, aspects that are challenging to capture within a metabolism model. These models are inherently quantitative, but there are qualitative and complementary approaches that can be employed to describe processes beyond mere numbers.

5. Conclusions

In this paper, we addressed the call made by Bahers et al. [15]. to explore how space is leveraged in urban design to impact the metabolism of urban projects and the objects they engender. To achieve this, we collaborated with designers and utilized an actual urban design project to exemplify how the concept of metabolism can be applied under real conditions and to evaluate its effects on the Champs–Elysées. Our findings reveal that while the impact of the design of public space on its metabolism is discernible, it remains limited in terms of reductions in resource consumption and negative metabolic effects. Acting on objects with higher metabolic activities and using more efficient technologies seems to be more fruitful in terms of adverse environmental impacts reduction, at least in this context. Again, this illustrated the constraints to significantly diminishing resource effects that designers confront when encountering partial aspects of urban circumstances.

For future research, it is crucial to recognize that the Champs–Elysées represents a highly distinctive and exceptional project, and it does not reflect a typical urban design scenario. Consequently, similar analytical approaches should be developed for other design circumstances, considering various territorial conditions both within France and elsewhere. By doing so, we will be able to advance our understanding of how urban design can better contribute to addressing resource and waste management challenges in diverse contexts.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su16020603/s1>. Supplementary Materials, as well as four Excel metabolic models, are available on request.

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