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Undoing the lock-in of suburban sprawl: Towards an integrated modelling of materials and emissions in buildings and vehicles

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A R T I C L E I N F O

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A B S T R A C T

Suburban sprawl emerged during the 20th century alongside the widespread ownership of cars. This type of low-density housing generates enduring car dependency due to the long lifetimes of buildings. A more sustainable mobility system would require a deep transformation to densify urban forms and thus foster proximity of homes, work, and services. Here we explore the evolution of long-lived residential building stocks and the potential for breaking of this lock-in by selective demolishing of detached houses to densify urban forms. We assess impacts on land use, material demand and stocks, and greenhouse gas emissions. We use a novel dynamic, Material Flow Analysis (MFA) model applied to a Swedish case study that accounts for the co-relations of building stock and car fleets through residential density. The model includes different municipality types and we explore three different speeds for the change in urban form. An accelerated densification requires more bulk materials in construction but fewer scarcer materials in cars. However, the up-front emissions of accelerated densification construction are only compensated by mobility savings in the long-term, by 2100. Emissions trends for the three scenarios are far from the urgent decarbonisation necessary. However, the denser final built environments may have social benefits and can free up significant land.

1. Introduction

Shelter and mobility represent 25% and 15% of household GHG emissions in consumption, respectively (Ivanova et al., 2016). There are significant scientific and policy efforts to reduce these emissions in the EU, including the energy efficiency of buildings directive (European Commission, 2021) and a ban on petrol vehicle sales by 2035 (The Council Of The European Union, 2022). The impacts and mitigation of these two sectors are mostly treated individually. However, buildings and vehicles are intrinsically interlinked. The home is considered a “pocket of local order” (Ellegård and Vilhelmson, 2004), where daily activities start and end. Daily mobility happens from and to home and is related to work and services in the same or nearest municipalities. Proximity to activities is constrained by urban form and requires a certain level of density. The low density and residential mono-functionality of suburban sprawl often require members of the community to own and frequently use private cars, increasing income requirements (Gössling et al., 2022) and the socioeconomic metabolic level of basic daily life (Ewing and Rong, 2008; Thomson and Newman, 2018). The expansion of suburban sprawl also: increases pressure on land use, decreases biodiversity, requires subsidies, and decreases access to services (Couch et al., 2006; Ewing, 1994; Güneralp et al., 2020). Dense and mixed-function urban areas generally increase public transport use and walking (Ewing and Cervero, 2010; Gascon et al., 2019, 2020; Jacobs, 1961; Miralles-Guasch, 2002; Newman and Kenworthy, 2006).

A very large proportion of the existing built environment was created after the introduction of the car. Suburban sprawl appeared in the post-WWII in the US, hand in hand with the diffusion of car ownership (Hayden, 1984, 2002; Levinson and Wynn, 1963; Urry, 2004). The long lifetimes of buildings and infrastructure in the built environment give these car-centric arrangements a large inertia and set conditions for their future use and resource consumption. While car fleets and ownership can change relatively quickly, the renewal of housing and other facilities cannot. For example, in developed countries like Sweden, car fleets are renewed every couple of decades (Morfeldt et al., 2021) hence the electrification of fleets is important in the mid-term. In comparison, the built environment has expanded continuously in the last century, accompanied by relatively minor demolition (Sandberg et al., 2016; Statistics Sweden, 2020, 2021). This generates few opportunities for

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deep transformation due to the large inertia of the building stock.

While extending durability is considered as a key strategy for sustainability for devices and infrastructure with large embodied impacts and material use and in mature energy-consuming technologies without significant efficiency improvements (Glöser-Chahoud et al., 2021; Hertwich et al., 2019; Skelton and Allwood, 2013; van Nes and Cramer, 2006), the building stock does not only commit emissions due to its own operation but also from the accompanying mobility system. We need a broader scope to address the connection and influence between systems. Further extending the useful lives of buildings to pay off their initial investment of embodied emissions and construction materials could potentially result in greater vehicle emissions and material use over time. Conversely, demolishing buildings and building more compact communities would mean greater emissions and material use, but lower emissions in mobility demands.

This lock-in of the built environment towards mobility is analogous to carbon lock-ins of other types of infrastructure. That is, infrastructure that is either used and which drive emissions or that become retired and are stranded assets (Fisch-Romito et al., 2021; Seto et al., 2016; Unruh, 2000). While lock-ins have been thoroughly analyzed for energy systems such as coal power plants (Cui et al., 2019; Davis et al., 2010; Hauenstein, 2023; Tong et al., 2019) and for iron and steel (Vogl et al., 2021), there has been very little attention to the quantification of urban lock-in, which may have even longer lifetimes and inertia.

Reyna and Chester (2014) explained the lock-in of energy efficiency and challenges to expanding the residential stock in Los Angeles. On smaller scales, previous research quantified induced mobility impacts (manufacturing and operation) with Life Cycle Assessments (LCA) of existent or newly built residential buildings (Anderson et al., 2015; Bastos et al., 2016; Lara Allende and Stephan, 2022; Lausselet et al., 2021; Nichols and Kockelman, 2014; Norman et al., 2006; Saner et al., 2013; Stephan et al., 2022; Treolar et al., 2000). Integrated LCA assessments of buildings and transportation show the significance of mobility in environmental impacts. For example, 62% of GHG emissions are mobility-related in a Norwegian "net-zero emissions" neighbourhood (Lausselet et al., 2021), and about half of the life-cycle emissions in the 3 types of districts in the urban region of Munich, Germany (Anderson et al., 2015). Despite this emerging LCA literature, the transformation of the built environment for new mobilities has yet to be explored, especially at-scale. Densification of buildings and neighbourhoods has been addressed in LCA but not considering the effects on mobility (Allan et al., 2022; Meier-Dotzler et al., 2021).

Material Flow Analysis (MFA) has been used to address the past and possible futures of building stocks and their effects on material use and GHG emissions (Cabrera Serrenho et al., 2019; Fishman et al., 2021; Hingorani et al., 2023; Lausselet et al., 2020; Müller, 2006; Oorschot et al., 2023; Pauliuk et al., 2021; Yang et al., 2022; Zhong et al., 2021), and separately for car fleets (Billy and Müller, 2023; Fishman et al., 2021; Morfeldt et al., 2021; Nakamoto et al., 2019; Pauliuk et al., 2012, 2021; Roca-Puigròs et al., 2023; Serrenho et al., 2017). Such MFA studies often include exogenous material efficiency strategies, and don't consider the constraints and co-relations that housing sets on mobility or vice versa. For instance, while vehicle use and ownership could decrease through cultural shifts, structural urban transformations that reduce the distance to activities by increasing density might be necessary to reach larger reductions. Lanau et al. (2019) reviewed the MFA literature on built stocks and highlighted that there has been a focus on construction materials and a lack of analysis of urban form and lock-in effects.

These research approaches have different comparative advantages that can help fill research gaps: the geography literature explains the relationships of urban form and mobility; LCA can quantify transport emissions in the assessment of existing residential buildings (but has not assessed urban transformation); MFA models explore possible futures of buildings and transport, but so far only with exogenous assumptions and not in a sectorally integrated way. In this study, we combine these approaches to endogenously consider the joint dynamics of both buildings and transport sectors using an integrated model.

We use the case study of Sweden's municipalities from 2020 to 2100, divided into 10 municipality types. This integrated dynamic MFA includes apartments, single-family houses, and cars. We calculate GHG emissions and materials in car production and use, and dwelling construction. To the best of our knowledge, this is the first attempt to assess a country-wide long-term densification strategy incorporating the interactions of buildings' and vehicles' emissions. Specifically, we analyze the dilemma faced when considering whether to demolish infrastructure to densify urban forms for enabling active mobility and public transport. We explore potential futures by considering different speeds for demolishing and building different types of new buildings along with other critical factors, with three scenarios with different speeds of demolition of single-family housing and shares of construction of single-family houses and apartment buildings.

2. Methods

2.1. Model

Our model integrates the dynamics of residential buildings (apartment buildings and houses) and cars (Fig. 1) to estimate the emissions of car production, car use (direct and indirect), dwelling construction, and

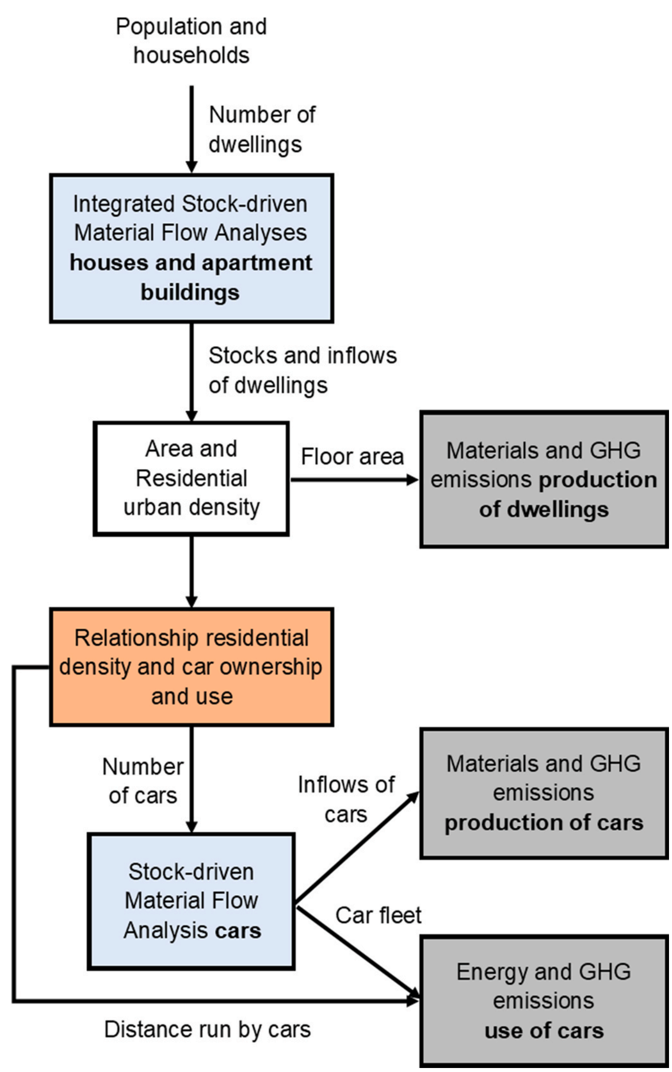

Fig. 1. Information flows between main blocks of the integrated model of residential buildings and cars. Grey boxes refer to final results and blue boxes to Material Flow Analysis. Orange box refers to the relationships in Fig. 2.

materials in dwellings and cars from 2020 to 2100. Code and data are available under an open source license (https://github.com/lapersanc/dMFAResMob). We use a very long-term, 80-year perspective despite its uncertainties so we can capture the long lifetimes of buildings. This way, we can analyze the evolution, inertia, and legacy of a mature building stock through different demolishing speeds and type of buildings in new construction. Sweden's building stock is considered mature because the country's population growth is expected to be limited.

The model is driven by population and household size, which define the number of in-use dwellings. This information forms the input for the residential building stock sub-model, which is split into two: houses and apartments, each with its own stock-driven dynamic MFA. A methodological addition to our dynamic MFA is that the speed of new construction is limited by the construction sector's capacity to avoid unfeasible and unrealistic peaks of construction (see SI section 2.3 for details).

We then calculate the floor area and residential urban density from the outputs of the building stock sub-model. Here, urban density refers to the number of inhabitants per residential land use. We propose a first attempt to model endogenously the relationship of building stocks to car use and ownership through residential density using logarithmic and polynomic relationships (Fig. 2). This follows the approach of other studies that showed the link of area per capita or density to energy use in mobility for global (Newman and Kenworthy, 1989), Swedish (Næss, 1993) and Nordic cities (Næss et al., 1996). Though density is essential for mixed uses, walkability and access to public transportation, other factors are also important, for example, road design, bicycle infrastructure and culture (Cass et al., 2005; De Witte et al., 2013; Gómez-Varo et al., 2022; Rinkinen et al., 2021). These additional design factors are out of scope here as we are focussed on high level urban transformation and car use.

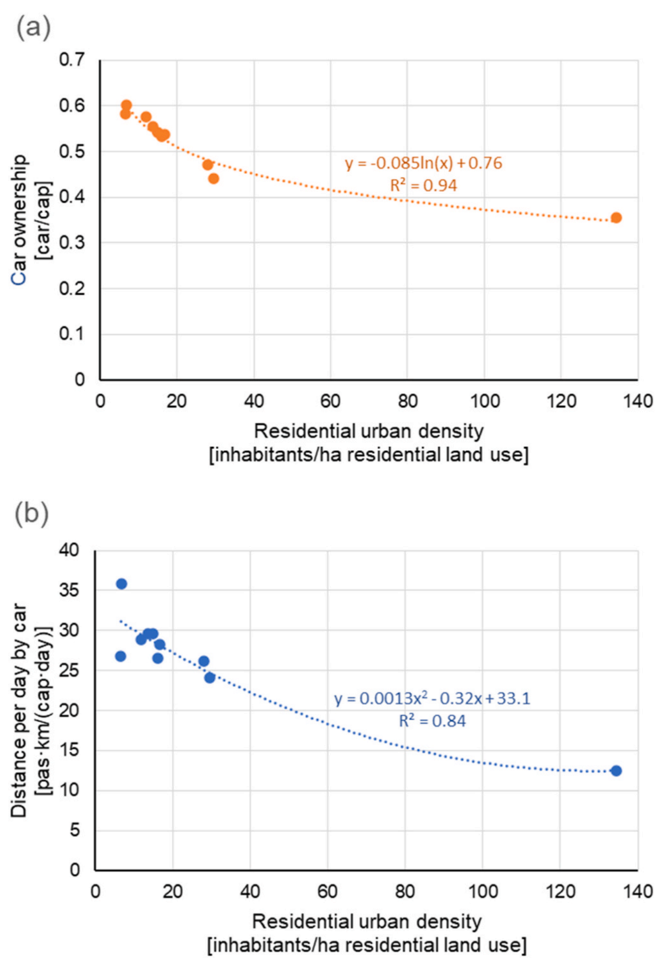

Fig. 2. Cars per capita and distance travelled by car per capita by residential urban density per municipality type (2015). Calculations are detailed in the supplementary information.

The number of cars is an input to the vehicles sub-model, which is also a stock-driven dynamic MFA. Multiplying the number of cars with the average mass of new cars per type of powertrain, we obtain the total mass of new cars. Through material intensities (kg material/kg car and kg material/m^2 dwelling), we obtain the disaggregated material requirements of buildings and cars per type. We then calculate the GHG emissions of production from emission intensities (kgCO$_{2e}$/kg car and kgCO$_{2e}$/kg material). Finally, we calculate the operational emissions of cars via fuel economies (MJ/veh·km) and emission intensities (kgCO$_{2e}$/MJ) for tailpipe and background energy system (the electricity mix and fossil fuel extraction and refining).

2.2. Case study

We focus on the case study of Sweden given the interesting characteristics of its urban environment and its relatively high data availability. While 80% of the population is considered urban, 53% of people in Sweden lived in single-family houses in 2020 (Eurostat, 2022a) and urban sprawl has been expanding in recent decades. The role of densification is also important in the Scandinavian context as Nordic countries have been working on re-densification in cities like Oslo, Copenhagen and Helsinki (Næss et al., 2011; Tiitu et al., 2021).

Sweden also has fine-scale data at the municipal level - the level at which most daily mobility functions operate. We apply the model to the 10 aggregated sets of municipalities following the Swedish classification in 2011 (Sveriges Kommuner och Regioner, 2023). This classification depends on the size of municipalities but also their economic activity and region type. Not all kinds of municipalities are included in the scenarios: Rural towns (8% of the population in 2015) are excluded because they are inherently low-density small settlements, and increasing their density would not offer improvements in mobility. Distances would remain the same as daily life activities might be carried out in other municipalities, and some economic activities, such as agriculture, are also low-density. We also exclude metropolitan municipalities (18% of the population in 2015) from the scenarios as they already have a very high share of apartment buildings.

2.3. Scenarios

2.3.1. Main densification scenarios

There are several different forms of densification. Residential urban density in inhabitants per hectare (inh/ha) depends on household size (inhabitants per dwelling), dwelling size (m^2 per dwelling) and the floor-to-land area ratio (m^2/ha). The latter two factors depend largely on the type of dwelling. Apartments are smaller than houses and have more floor area per building ground footprint.

We assess three densification scenarios based on substitution speed and ratio of single-family houses to apartment buildings: *Accelerated densification*, *Slow densification*, as well as a baseline called *Current values*. We set two exogenous variables: *type of new buildings* (k) and *lifetime of houses* (g) for each scenario (see Table 1, and a full codification

Table 1
Densification scenarios and assumptions.

Densification scenarios	Built environment	
	Type of new dwellings (k)	*Lifetime houses (g)*
Accelerated densification	100% apartments	Shorter (55 for newer houses and 120 for old houses)
Slow densification	100% apartments current values	Longer (120 years)
Current values	current values	Longer (120 years)

of model variables in the supplementary material). The *Accelerated densification* scenario describes shortened single-family house lifetime, making substitution faster and enabling mobility shifts but at the expense of embodied resources. The *Slow densification* scenario only employs higher density when new structures are built – building apartment buildings in place of lower-density housing when they need to be replaced. *Current values* assumes the same percentages of construction of houses and apartments as today, with relatively long lifetime of houses.

A number of premises are the same for all three main scenarios based on the Swedish context and upcoming policies and goals, which define the remaining exogenous variables. According to Eurostat estimates, Sweden's population will grow to 12 million by 2100 (Eurostat, 2022b). However, household size is stagnant. We assume a ban on new internal combustion car sales by 2030 which leads to full electrification of the fleet before 2050. Another factor is the already low-carbon intensity of the Swedish electricity mix. These settings are kept the same across scenarios, yet the effects of some of these factors are further explored as part of a sensitivity analysis described below. We also assume that construction technologies and material composition in buildings and cars are constant. This also means that a decarbonisation of the electricity mix is not reflected in the emissions in the production of buildings and cars.

2.3.2. Sensitivity analysis

To explore how different contexts could affect the outcomes of densification, we conduct a sensitivity analysis and re-run the three main densification scenarios by varying four different input parameters, yielding a total of 15 (3 × 5) scenarios (Table 2). These assumptions include: L*onger lifetime of buildings*, *More intensive use*, *EU electricity mix,* and *Non-electrified fleets*.

The sensitivity of *Longer lifetime of buildings* is tested because the durability/mortality of the buildings is one of the most uncertain variables, with little availability of benchmarks in the literature (Aksözen et al., 2017; Sandberg et al., 2016). Most of the stock built in the 20th century is still in place and built since the 1960s (Sandberg et al., 2016; Statistics Sweden, 2020, 2021). Very few buildings have reached their end of life and demolishing them is mainly related to functional and locational obsolescence (Thomsen and Van Der Flier, 2011).

More intensive use directly affects residential density and service level at low or no-investment costs. Sweden has a smaller occupation of buildings and cars than the rest of the world (Eurostat, 2022c; Fiorello and Zani, 2015). We increase gradually household size from 2.1 to 2.5 persons per household (similar to countries like Portugal and Spain (Eurostat, 2022c)), and the occupancy rate of cars from 1.3 to 1.8 persons per vehicle (see SI). These are related to the de-individualization of daily lives and to a decrease in the size of new cars, which are among the largest in Europe (ICCT, 2021).

The *EU electricity mix* has the same built environment and service level as the central scenario, and only affects GHG emissions. Electricity mix has been highlighted as one of the main parameters affecting the carbon footprint of electric vehicles (Cox et al., 2020; Mendoza Beltran et al., 2020). The Swedish electricity mix is based on nuclear, hydro and wind power, with relatively low GHG emissions intensities compared to other European nations (at 8.8 $kgCO_{2e}/kWh$ in 2020 (European Environment Agency, 2021)). As such, we also explore the outcome of densification with an average EU electricity mix in 2020 (230 $kgCO_{2e}/kWh$ (European Environment Agency, 2021)), decreasing linearly to 0 in 2050 to explore the dynamics that could be expected elsewhere.

Non-electrified fleets also has the same built environment set-up but uses the 2020 powertrain shares of new cars as the values over the whole time series. In this case, car fleets will not be fully electrified and will maintain a variety of powertrain types with larger direct tailpipe emissions.

3. Results

3.1. Stocks

The three scenarios show large differences in final stocks with very different built environments (Fig. 3). Residential density sees the largest variance of the other results, starting at 22 people per hectare in 2020 and finishing at 30 people/ha in *Current values*, 38 in *Slow densification*, and more than doubling in *Accelerated densification* (51 people/ha). The effect of the lifetimes and construction types in the scenarios is reflected in the evolution of the residential density (Fig. 4). The relatively sudden active transformation of the built environment through the shortening of lifetimes of single-family housing makes that the *Accelerated densification* increases density right at the beginning of the period. In the other two scenarios, changes are slower and mostly due to the expansion of the stock and not due to the substitution of single-family housing into multi-family dwellings due to the large inertia of existent long-lasting stocks. These densities can be translated into the share of floor area in multi-dwelling buildings. In 2020, 39% of the residential floor area are flats, which by 2100 reaches 53% in *Current values* and 76% in *Accelerated densification.*

These higher residential densities entail a shrinking in the residential land use for all scenarios, despite the increase in dwellings (from 4.8 M to 6.3 M dwellings). By 2100, *Accelerated densification* (267 kha) requires only around half of the initial 2020 land use (480 kha). For perspective, the total built land in Sweden in 2015 was 1.3 Mha, and the total arable

Table 2
Sensitivity parameters of longer lifetime of buildings, more intensive use, EU electricity mix, and electrification of the fleet, including the affected inputs to the model. Shaded cells in grey determine the common values to the main scenarios. Lifetime of single-family houses changes according to each of the three densification scenarios.

		Main scenarios	Sensitivity parameters			
			Longer lifetime of buildings	More intensive use	EU electricity mix	Non-electrified fleets
Families	*Household size (b)*	current values	current values	larger	current values	current values
Lifetime buildings	*Lifetime flats and houses (f and g)*	densification scenarios	longer	densification scenarios	densification scenarios	densification scenarios
Cars	*Occupancy rate (am)*	current values	current values	larger	current values	current values
	Size of cars (ae)	current values	current values	smaller	current values	current values
	Type of powertrain of new cars (af)	all BEV by 2030	all BEV by 2030	all BEV by 2030	all BEV by 2030	current powertrain shares
Electricity mix	*Emission intensity - fuel cycle/electricity mix (av)*	Sweden	Sweden	Sweden	EU	Sweden

			2020	2100			Difference 2100-2020		
				Current values	Slow densif.	Accel. densif.	Current values	Slow densif.	Accel. densif.
Residential density		people/ha	22	30	38	51	39%	76%	138%
Land Use		kha	480	458	361	267	-5%	-25%	-44%
Floor Area	Total	Mm^2	443	540	504	475	22%	14%	7%
	% in flats	%	39%	53%	65%	76%	35%	67%	95%
	per capita	m^2/cap	43	39	37	35	-8%	-14%	-19%
Stocks	Dwellings	million	4.8	6.3	6.3	6.3	32%	32%	32%
	% of flats	%	59%	67%	77%	85%	13%	31%	44%
	Cars per capita	car/cap	0.48	0.45	0.43	0.40	-6%	-10%	-17%
	Cars	million	5.0	6.2	5.9	5.5	24%	19%	10%
Travelled distance by car	per capita	pas·km/(cap·yr)	8821	8553	7897	6672	-3%	-10%	-24%
	per car	veh·km/(cap·yr)	14175	14654	14130	12880	3%	0%	-9%

Fig. 3. Initial (2020) and final conditions (2100) of the three scenarios. Coloured bars with the same colour are at the same scale. The colors in the two columns at the right indicate: Orange-smaller values than Current values, white-no difference, and blue-larger values.

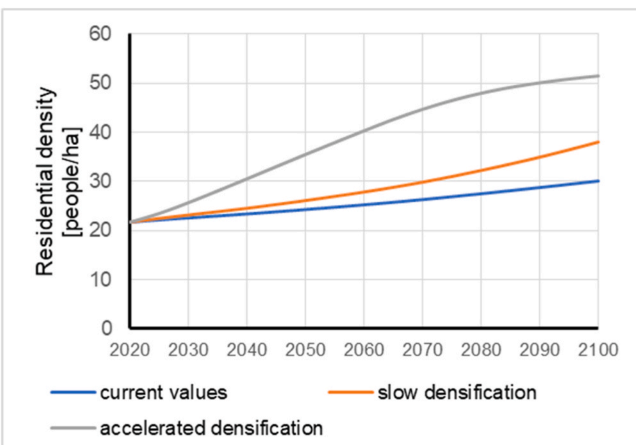

Fig. 4. Evolution of residential density in the three main scenarios (2021–2100).

land 2.4 Mha (Statistics Sweden, 2018). These changes free up 0.2 Mha of residential land use, representing a substantial saving. These reductions would be larger if we considered the land use of roads and streets. Nevertheless, the freed area is minor in the context of the whole country (41 Mha of total LU).

These different final urban forms drive significant changes in car ownership and use. By 2100, Swedish inhabitants in the *Accelerated densification* scenario would travel about 2000 pas·km/year per capita less (−25%) and own 0.7 M fewer cars (−11%) than in the *Current values* scenario. The rise in residential density is much larger than the reduction in car ownership and use. The distance travelled by car per day saturates at about 100 inhabitants/ha of residential urban density (Fig. 2).

3.2. Cumulative flows

Fig. 5 shows the total invested materials, produced items and GHG emissions accumulated between 2021 and 2100 in the three scenarios. In the *Accelerated densification* scenario, more new buildings are required, resulting in more construction materials. There are also more demolished houses. The large amounts of materials in demolition are likely not directly reusable or even fully recyclable (except for downcycling) in new buildings since architectural design does not generally consider end-of-life (e.g. most buildings are not built with reuse in mind via standardized and demountable elements) (Adams et al., 2017; Cooper and Allwood, 2012; Dunant et al., 2017).

The cumulative emissions for the three main scenarios follow similar trends and reach ca. 550 $MtCO_2e$ by 2100. No scenario meets the required reduction in emissions for net-zero goals (Fig. 6). There is very little discernible difference in cumulative GHG emissions to 2100 between the *Current values* and *Slow densification* scenarios, while the *Accelerated densification* scenario stays slightly above *current values*. By 2060 the savings in mobility start to be large enough to begin to catch up with the other two scenarios and by 2100 they are equivalent in emissions (SI: Fig. S9). This shows that *Accelerated densification* is a very long-term investment and strategy. The intensive transformation in *Accelerated densification* is not fast enough to guarantee sufficient savings in mobility to pay off the investments in construction under the conditions described by this scenario.

Emissions of car use are similar in the three scenarios due to fleet electrification, which happens parallel to building densification but is completed much earlier. There are a similar number of cars and driven distance in the first years of the three scenarios, when there are still larger GHG car use emissions due to the internal combustion powertrain types. When electrification is completed, the savings in the travelled distance do not reflect in savings in GHG emissions given the lack of tailpipe emissions and the low-carbon electricity mix. As a result, densification only saves emissions in the first few decades in terms of car use, while there are ICV cars in the fleet. This way, car production becomes the highest source of emissions of the four stages we considered in the model.

3.3. Which factors influence the results?

Different contexts impact the effects of densification, and we examine the sensitivity of the results to variants of four parameters as described in the methodology section (Fig. 7). Two parameters directly affect the number of dwellings and cars: *Longer lifetime of buildings* and *More intensive use*. The other two parameters (*Non-electrified fleets* and *EU electricity mix*) relate to the type of cars and the electricity mix, which directly affect GHG emissions.

Among these four parameters, *Non-electrified fleets* (2020 powertrain shares of new cars as the values for the whole time series) is the only one provides significant GHG savings in the *Accelerated densification* scenario compared to the *Current values* scenario (−13%). In the *Non-electrified fleets* variant, the *Acelerated densification* scenario generates lower yearly emissions than current values around 2035. In the main scenario, with the electrification of the car fleets, *Accelerated densification* only generates lower emissions from 2060 on, when yearly emissions are already low for the three scenarios (SI Figure S9). The electrification of fleets in

			Total (2021-2100)			Difference to current values	
			Current values	Slow densif.	Accel. densif.	Slow densif.	Accel. densif.
Construction	Area	million m^2	263	224	258	-15%	-2%
	Flats		163	207	242	27%	48%
	Houses		99	16	16	-84%	-84%
	Dwellings	million dwellings	3.2	3.2	3.7	-1%	15%
	Flats		2.4	3.1	3.6	27%	49%
	Houses		0.8	0.1	0.1	-84%	-84%
Demolition	Dwellings	million dwellings	1.7	1.6	2.2	-1%	31%
	Flats		0.7	0.7	0.7	0%	1%
	Houses		0.9	0.9	1.4	-3%	55%
Production	Cars	million	26.6	25.9	24.0	-2%	-10%
Distance travelled by car	by people	pas·km	8771	8494	7373	-3%	-16%
	by cars	veh·km	6747	6534	5671	-3%	-16%
Emissions	TOTAL	MtonCO$_{2e}$	561	565	562	1%	0%
	Car production		255	248	230	-2%	-10%
	Car use - direct		164	164	162	0%	-1%
	Car use - indirect		51	51	51	0%	-2%
	Dwelling prod.		109	118	138	9%	27%
Material inflows	Dwellings	Mton	186	199	232	7%	24%
	Cars	Mton	48	46	43	-2%	-10%
	lithium	kton	262	255	236	-3%	-10%

Fig. 5. Total invested resources and produced items in the three scenarios (2021–2100). Coloured bars with the same colour are at the same scale. The colors in the two columns at the right indicate: Orange-smaller values than Current values, white-no difference, and blue-larger values.

the context of a low-carbon electricity mix reduces emissions. This generalised emission reduction in all 3 main scenarios means there are insufficient emission savings via decreased travel distance that balances out the investments in densification. Overall, electrification of the fleet plays a large role in emission mitigation and makes the densification strategy less effective. While this may be expected, this happens even with an initial electricity mix with a higher carbon intensity (*EU electricity mix*). Since the car fleet is electrified simultaneously with the decarbonisation of the electricity mix, the impact of the high emission intensity in the first years is minor.

With other material efficiency strategies such as increasing lifetime of buildings or the combination of larger household sizes, smaller cars and larger occupancy rates, the number of constructed dwellings decreases sharply (by 1 million). However, while dwellings are very sensitive to *Longer lifetime* and *More intensive use*, GHG emissions are not. The emission trajectories are also similar between densification speeds. In the end, densifying more or less quickly generates a similar amount of emissions at the end of the time interval of analysis.

4. Discussion

An accelerated transformation of the built environment implies larger upfront emissions in construction, though it generates savings in car production and use in the long term. However, the scenario results are somewhat counterintuitive. Despite the very different scenarios investigated, overall emission trends are similar and do not move towards the needed net-zero goals. However, the three scenarios do have very different material and land implications. Urban densification frees up of considerable amounts of land, halving land use compared to today. The saved land could be even greater if we included the saved land for roads and streets. This freed-up area is close to where people live and could be used for recreation, carbon sequestration, local food production, and more.

The different scenario results show a trade-off between the demands for materials in buildings and in cars. An accelerated densification requires larger material inflows for buildings (compared to the current construction rates), while it curbs demand for car materials including critical materials such as lithium. The supply of both critical materials and some bulk materials, such as sand, may be an issue in the future (Calvo and Valero, 2022; Churkina et al., 2020; de Blas et al., 2020; Ortego et al., 2020; Zhong et al., 2022) and therefore, policymakers should take into account both types of materials. However, a faster change of the built environment could also be an opportunity to design with new construction methods, production processes, materials, and layouts that enable sharing, flexible housing, etc. and therefore generate further social changes for sustainability (Pérez-Sánchez et al., 2022).

The physical changes in the built environment entail changes in social practices. By 2100, travelling decreases substantially in the *Accelerated densification* scenario, by around 2000 pas·km per capita and year less than *Current values*. The decrease in car ownership is not as substantial. The relationship between car ownership and density in Fig. 2 shows how the increase in density entails a more significant decrease in car use than in ownership. Metropolitan city dwellers still own cars even though they don't use them as often. Car ownership and use could be reformulated with cultural changes that are fostered in the favorable context of denser cities (e.g., carpooling, access to public transport and services). Car travel also depends on many other economic and cultural factors that are out of scope in this study. Our results are therefore first-order assessments of the direct influence of urban form on car use. While this relationship is robust, future research could add these other factors.

The results do not provide any clear policy direction to follow. Instead, they underscore the challenge of the deep transformation of the

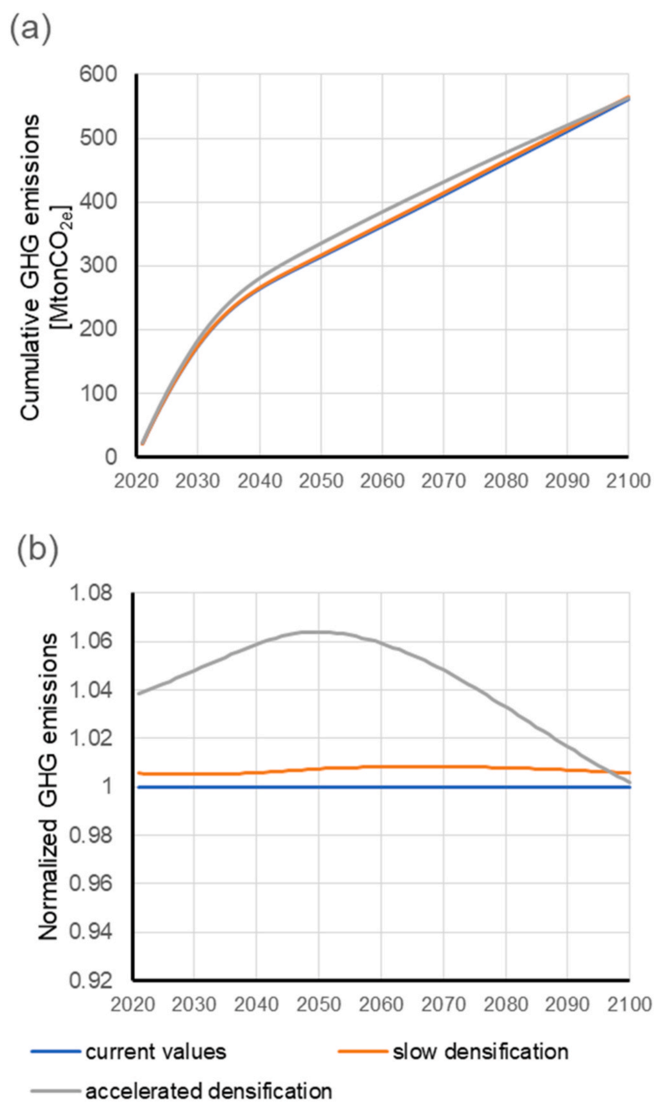

Fig. 6. (a) Cumulative and (b) normalized to "current values" GHG emissions of the three main densification scenarios (2021–2100).

built environment and the need for further research. The long lifetimes of buildings generate lock-in that affects daily life and its concomitant resource use and impacts. The densification of suburban sprawl is a long-term and gradual process. While each newly constructed multi-family building is a necessary step towards a denser built environment in the mid-term, it is a small contribution to a mature stock of buildings in the short term. This addition can change very little the average density of a municipality. Sustainable futures depend on the slow and investment-heavy transformations of the current building stock or on the possibility of changing daily life in existent built environments. For example, the paradigm of 15-min neighborhoods is not compatible with current large extensions of suburban sprawl. We must envision and plan sustainability futures to new sociometabolic regimes considering the existing enduring infrastructure that locks-in car dependency.

4.1. Modelling limitations and constraints

We propose a novel model for analysing, and providing an outlook on, the evolution of residential urban form and mobility. We present a case study as a first step and describe potential limitations. This study proposes a novel model for integrating dynamic material flow analyses of building stocks and of car fleets and their use through urban density. We produce these underlying relationships based on data from a single year, 2015 (cf. Fig. 2). Many aspects could alter this relationship: cultural changes such as a reorganization of work closer to homes, and other structural strategies such as increase of provisioning of public transport. Also, density is not the only parameter defining mobility. Therefore, while 2015 can be considered a representative year of current buildings-vehicles ratios, this relationship could be made more dynamic and cover more complexity as data become available.

The long time horizon of analysis (2100) is necessary for analysing the evolution of building stocks due to long lifetimes, but it inherently amplifies uncertainties of modelling far into the future. We did not explore possible changes in material intensity and other construction methods and design choices, to constrain the number of scenario variations. These values were taken from the most current available data for Sweden and had higher values of material intensity ($kg/m^{2)}$ for apartment buildings.

The boundaries of the system could also be extended to account for further products, sectors, and processes. For example, we did not include road stocks and public transport modes, and end-of-life in the assessment. Our analysis is limited to first-order direct effects of how investments in densification can provide substantial changes in private mobility. However, these scenarios cover the major impacts from buildings and vehicles. Also, our methods allow for further environmental benefit analysis of potential impacts other than GHG emissions.

5. Conclusions

In this study, we explored the dilemma between increasing building lifetime at the expense of maintaining suburban sprawl. This dilemma represents a lock-in of car use and land use based on urban form. Lock-in has been previously analyzed quantitatively for energy systems and power plants. However, to the best of our knowledge, this is the first study that explores this concept quantitatively for profound structural transformations of the built environment. This includes a first attempt to link urban form to car use and ownership in MFA. We explore possible futures of building stocks, their inertia and lock-in through urban density. This parameter allows us to analyze the combined effects of densification strategies on the future building stocks and car fleets, and their impacts on GHG emissions, materials, and land use. We move beyond modelling individual sectors in terms of their own resource flows and emissions to explore interdependencies and potential trade-offs of multiple sectors.

We use a Swedish case study due to the relevance of densification in the Nordic context and the availability of data at the municipal level. This kind of transformation could be further explored in countries with even lower residential density and higher car dependency, such as North America or the UK. The scope of the model could also be extended to include other factors, such as roads, public transport, and maintenance and end-of-life of buildings and cars. Further work could also explore the effects of alternative construction methods with lower impacts.

This model represents a first step for exploring deep transformations of the built environment to enable new lives and economies. Densification would also affect other daily practices and the economy, which are outside of the scope of this model, such as: create collective spaces, the shareability of devices (e.g., carsharing and carpooling: increasing car occupancy), and increase social interaction. The ultimate sustainability challenge is to generate coherent configurations of the economy and communities with a lower metabolism. This might require entirely new infrastructures and large investments to reconfigure society's fundamental structures.

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Sensitivity context	Densification scenarios	Dwellings	Cars	Materials dwellings	Materials cars	Lithium	GHG emissions
		million	million	Mton	Mton	kton	$MtonCO_{2e}$
Main scenarios	current values	3.2	26.6	186	48	262	561
	slow densification	3.2	25.9	199	46	255	565
	accelerated dens.	3.7	24.0	232	43	236	562
Longer lifetime buildings	current values	2.0	27.0	118	48	267	526
	slow densification	2.0	26.7	125	48	263	527
	accelerated dens.	2.9	24.5	183	44	240	538
More intensive use	current values	2.1	26.0	123	42	232	468
	slow densification	2.1	25.6	132	42	228	471
	accelerated dens.	2.6	23.6	165	38	209	470
EU electricity mix	current values	3.2	26.6	186	48	262	601
	slow densification	3.2	25.9	199	46	255	604
	accelerated dens.	3.7	24.0	232	43	236	599
Non-electrified fleets	current values	3.2	26.6	186	44	51	1665
	slow densification	3.2	25.9	199	43	49	1625
	accelerated dens.	3.7	24.0	232	40	46	1454

Fig. 7. Impacts of the sensitivity parameters (total 2021–2100). Coloured bars with the same colour are at the same scale. Cells with grey background indicate same values as "Main scenarios".

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CRediT authorship contribution statement

Laura À. Pérez-Sánchez: Writing – original draft, Visualization, Software, Methodology, Data curation, Conceptualization. **Tomer Fishman:** Writing – review & editing, Methodology. **Paul Behrens:** Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Code and input data are available in https://github.com/lapersanc/dMFAResMob.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141954.

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