Energy Performance Comparison of a High-Density Mixed-Use Building To Traditional Building Types

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Abstract

This paper applies an urban simulation tool to explore the impact of density on operational and embodied energy and carbon using parametrically-generated models. The models were created using Grasshopper and Rhinoceros 5, and the simulations were performed by the Urban Modelling Interface (UMI). A high-density mixed-use building housing 10,000 residents is compared to base cases of traditional building use types housing the same population. The retail and office space of the mixed-use building is also compared to typical local retail and office building types. Building shape, insulation levels and structural materials were also varied to analyse their affect. Results showed that of the base cases, highly insulated low-rise apartments had the best performance at 67% and 50% reductions over to-code insulated single detached homes. Of the large mixed-use building cases, they all had similar energy reductions to low rise apartments but due to utilizing concrete, their embodied energy and carbon were much higher. The timber framed versions of the mixed-use cases achieved better energy performance and cut their embodied energy and carbon by over 70%. Important results were that as buildings become much more energy efficient, the proportion of energy and emissions embodied in the materials becomes significant. Overall building form, as well as the construction material must be considered to minimize energy use and emissions.

Introduction

The global population is expected to increase to 9.8 billion by 2050 according to United Nations (2015), requiring ever increasing amounts of housing and other amenities. Studies have also shown that an increasing percentage of the population is living in urban areas (United Nations, 2018).

As a result, it is of critical importance that as cities either expand or densify, that they do so in the most sustainable manner possible, while also providing high quality of life. However, growth is often uncontrolled, without a holistic development plan and this can result in urban sprawl. Urban sprawl can be defined as a "particular type of suburban development characterized by very low-density settlements, both residential and non-residential; dominance of movement by use of private automobiles, unlimited outward expansion of new subdivisions and leapfrog development of these subdivisions; and

segregation of land uses by activity" (White et al. 1974). Neighbourhoods are typically not as walkable with poor public transit.

Urban sprawl has many negative impacts, including increased congestion and emissions that result from increased personal vehicle use and idling. Additionally, human health is typically negatively affected by urban sprawl (Ewing et al. 2014; Ewing et al. 2016; Zhao and Kaestner, 2010). Neighbourhoods not being walkable leaves fewer alternatives to driving, whereas when amenities are within walking distance, residents can walk or bike to destinations which increases physical health.

A less obvious consequence of urban sprawl is efficiency, both in terms of energy and materials. Having lower density housing means that the buildings are spread out over larger areas. This increases the cost of infrastructure that is needed to provide basic services. Lower density housing also increases the building envelope surface area, as more buildings are needed to house the same number of people. This increases the heat losses through the building envelope, increasing energy use.

There have been studies that examine urban sprawl and evaluate different potential solutions that can be implemented to avoid or correct it. One solution that shows promise is "smart growth" using carefully planned higher density mixed use developments (Alexander and Tomalty, 2002; Daniels, 2001; Geller, 2003; Barbour and Deakin, 2012; Steemers, 2003; Jabareen, 2006; Ko, 2013). These combine denser housing in the form of apartments or townhouses with retail and office space. This has numerous advantages; higher density housing means less heat loss through building envelopes, and lower costs to provide services due to a more concentrated population.

This paper explores an extreme version of this approach called the "Mothership". A mothership is a high-density mixed-use development that is designed to provide all the amenities and housing of an entire suburb in one large building or cluster of connected buildings. The mothership is an attempt at combining the above topics of high density, mixed use, high efficiency energy systems, and transportation hub into a holistic solution to urban sprawl. It must be stressed that each of these components by themselves has been done before, and some combined together in the form of industrial and institutional campuses, the Apple Park being an example (Dezeen, 2019). However, there are few, if any studies which

attempt to quantify the performance of a mothership style building and compare it to the performance of traditional building use types for the same number of residents.

The analysis performed in this paper attempts to quantify these differences in energy and emissions metrics, by parametric analysis of building dimensions, construction standards, and materials. Transportation analysis as well as energy system analysis and optimization are beyond the scope of this paper but are considered for future work.

Method

The overarching methodology for this project is to quantify and compare the benefits and disadvantages of high density mid-rise single mixed-use buildings with the typical building archetype base cases. This is executed through creating parametric models of different traditional building use types to create scenarios in which performance will be compared to the mothership. Each scenario will house the same number of people (10,000). In each of the scenarios, the number of buildings modelled will be the number required to house this population, using the average residents per housing unit values in Canada for each building type (Natural Resources Canada, 2014).

The building geometry was created in the 3D CAD environment Rhinoceros 5 (Rhino), using the Grasshopper plugin. Grasshopper is a visual programming language that allows designers to create parametric models using numerical sliders as inputs. The sliders can be used to change the input values and see the resulting geometry changes in Rhino in real time. Parametric models creating the building geometry were created with parameters such as width, length, and the number of floors of the different use types.

The building simulation is performed using another Rhino plugin, the Urban Modelling Interface (UMI) (Reinhart et al. 2013), developed by the Sustainable Design Lab at MIT. UMI specializes in urban scale environmental performance of neighbourhoods and cities using several metrics such as energy use, daylighting potential, walkability, and embodied energy and carbon. Building specifications such as materials, constructions, schedules and climate can be assigned to each building geometry in Rhino.

The energy simulation is performed using EnergyPlus (US-DOE, 2019) through UMI. The advantage of using UMI is that it is much faster at simulating all the buildings in an urban area than using EnergyPlus to simulate them individually. It accomplishes this using the shoeboxer (Dogan and Reinhart, 2017), an algorithm that goes through the building and determines the most significant zones to model, and then interpolates between them for the rest of the zones. This process does sacrifice accuracy for speed, however when only estimates are needed in a preliminary design phase with many potential designs, it is a very powerful tool for honing in on the higher performing options. This is the reason that it was chosen for this analysis.

The metrics that will be used to assess the performance of the different cases are operational energy use (OE) (kWh/person), embodied energy (EE) (kWh/person), and embodied carbon (EC) (kg CO₂/person). These are calculated for a building life cycle of 60 years. The metrics are intensities per person, as opposed to per unit floor area, due to the different floor areas in the residential base cases (e.g. it takes more floor area to house the same number of people in typical single detached homes than typical apartments). The number of residents does not change between the scenarios; therefore, the values were normalized by number of residents.

Base Cases

The use types that will be examined are:

- single detached homes
- single detached duplexes
- low-rise apartments (5 storeys)
- medium-rise apartments (10 storeys)
- high-rise apartments (42 storeys)

The building envelope constructions were modelled at different levels. The first is typical to-code building practices for the east coast of North America's climate (UMI defaults). The second is super insulated, with wall and roof u-value of 0.022 W/(m²*K) (R40) and a floor u-value of 0.17 W/(m²*K) (R45). Another variation is the main structural materials, namely concrete/masonry or timber frame. Due to building codes, buildings above a certain height are required to be built using reinforced concrete. The height that this occurs, for our local building code (British Columbia Building Code or BCBC) is six storeys (BC Housing, 2009). As a result, mid-rise and high-rise apartment buildings are made using concrete, while the others are built using timber frame. The building parameters were left as the program defaults, with the exception of insulation. Table 1 summarizes the important default parameters, and what the insulation levels were changed to for the PH cases.

Table 1: Important modelling parameters for the default and passive house (PH) cases

Parameter	Default	PH Case
Wall Insulation [U-Value]	0.072	0.022
Roof Insulation [U-Value]	0.066	0.022
Floor Insulation [U-value]	0.08	0.17
Window U-Value	0.5	0.22
Infiltration Rate [ACH]	0.35	0.35
Ventilation Rate [ACH]	0.6	0.6
Heating Set Point [degrees C]	20	20
Cooling Set Point [degrees C]	24	24
Heating COP	0.9	0.9
Cooling COP	3	3

Since the motherships are mixed use and include some retail and office (RO) space as well as the residential space, base case buildings of these use types were also modelled. There are four RO archetypes, numbered one through four, and for each archetype there are six building

templates applied. The scenarios are named according to their space use type, whether they are super insulated ("PH" suffix) and whether they are built with wood frame construction ("WF" suffix) instead of concrete as the main structural material. The floor areas for the RO space base cases are the same as in the mothership's (50,000 m² each). The shapes chosen were meant to explore the

effects of different building massing, from large sprawling single level warehouse or mall typologies, to more compact four storey office buildings. A summary of the base case scenario parameters is shown in

Table 2.

Table 2: Dimensions, number and total area of buildings for each base case.

Use Type	X Dimension [m]	Y Dimension [m]	Height [m]	Number of Resi Floors	Number of Ret/off Floors	Number of Buildings	Total Building Area [m ²]
Single Detached	10	10	6	2	-	4,160	832,000
Duplex	13	13	6	2	-	2,304	778,752
Low Rise	26	26	15	5	-	160	540,800
Medium-Rise	26	26	30	10	-	64	432,640
High-Rise	23	24	126	42	-	29	672,336
RO 1	224	224	5	-	1	1	50,000
RO 2	50	50	12	-	4	5	50,000
RO 3	91	91	18	-	6	1	50,000
RO 4	25	25	60	-	20	4	50,000

Table 3: Dimensions, number and total area of buildings for each mothership case.

Use Type	X Dimension [m]	Y Dimension [m]	Height [m]	Inner Radius [m]	Outer Radius [m]	Number Resi Floors	Number Retail Floors	Number Off Floors	Number of Buildings	Total Area [m ²]	Residential Extension [m]	Terrace Width [m]	Terrace Offset [m]
MS1	50	50	30	n/a	n/a	8	1	1	20	500,000	n/a	n/a	n/a
MS3	100	63	30	n/a	n/a	8	1	1	10	500,000	n/a	25	5
MS4	100	50	30	n/a	n/a	8	1	1	10	500,000	n/a	n/a	n/a
MS8P	n/a	n/a	21	n/a	140	5	1	1	5	508,285	n/a	30	6
MS10	n/a	n/a	30	137	187	8	1	1	1	505,873	n/a	n/a	n/a
MS11	n/a	n/a	39	90	140	11	1.5	1.5	1	502,354	n/a	n/a	n/a
MS12	n/a	n/a	36	180	220	10	1	1	1	499,966	n/a	n/a	n/a
MS4 WF	100	50	18	n/a	n/a	4	1	1	10	500,000	66.66	n/a	n/a
MS10 WF	n/a	n/a	18	137	187	4	1	1	1	506,940	27	n/a	n/a

Motherships

The different mothership scenarios try to explore various ideas. The first, MS1, consists of simple rectangular structures arranged in a rectangle enclosing a large quadrangle, and MS3 uses the same design but with longer buildings arranged into two parallel lines of 5 buildings each. The second concept was to terrace the MS3 design by shifting each successive floor back from the face of the floor beneath it. This was done to increase daylighting and create private outdoor space. This had the trade-off of increasing the surface area and increasing energy use. Additionally, it creates a large open space in the interior of the building that would likely need to be lit with artificial lighting, further increasing energy use.

The third major design scenario was a ring shape, that was further explored in three different cases. The first case MS10 is 10 storeys, with an inner diameter of 137 m, and a floor width of 50m. MS11 increases the number of

floors to twelve, while keeping the overall floor area the same, thereby decreasing the radius. In the third case, MS12, the building width was decreased, to increase the daylight levels near the interior of the buildings. This causes the radius to increase to maintain the same floor area.

MS8 explores a dome shape, with each floor being terraced back from the one below it. This produces an interesting aesthetic, but poses some design challenges, the biggest of which is that the floor area on each level decreases substantially with each successive floor. This means that the radius needs to start larger or have multiple buildings. This also creates a large amount of space in the interior that would be relatively difficult to provide natural daylighting to.

Typically, the first floor of the mothership is retail, the second floor is office space, and the ones above are residential. Some of the more complicated shapes are

configured differently but the floor areas remain the same. As with the base case models, the construction materials were also varied. All mothership scenarios are super insulated, to the same extent as the other PH scenarios. Table 3 gives the list of parameters used for each of the mothership cases.

For designs that were over 6 storeys it was necessary to use concrete. However, others were built to six storeys using mass timber. The last two scenarios that were explored use mass timber for the main building material as opposed to using concrete. The reasons for this are mainly the reduced embodied energy and embodied carbon of the building material when compared to concrete. However, there are other benefits of mass timber, some of which are outlined in Sorenson (2016), Kremer and Symmons (2015), Naturally:Wood (2016a), Naturally:Wood (2016b), and WoodWorks (2019). The main downside of building with mass timber currently is the limit to six storeys according to local building code, when the mothership design is built to 10 storeys. This height limit means that the floor area of 4 residential floors need to be made up by increasing the building footprint. This increases the surface area and heat transfer losses through the building envelope. For this reason, wood frame versions of MS4 and MS10 were simulated, to see if this increased surface area had an impact and to compare the reductions in EE and EC to the other cases that used concrete.

Assumptions

UMI has components that should make it possible to run parametrically and automatically in grasshopper, but currently these are not functional at this time. As a result, the parametric models must have parameters modified manually using a limited range of values for the sliders. Ideally it would be possible to assign a larger range of values to each of the sliders and have a component that creates and runs models with all the permutations of these parameters. With this component it could potentially be able to use one of the built in Grasshopper optimizers to optimize the building geometry. However, this is not currently possible. An automatic way of varying the parameters and running the simulations is a topic for future work.

The values that UMI simulations output are estimates only and are not taken to be exact values. It is simply a good tool for quickly working through a design space, and once the best performing design is determined, dedicated specialized software should then be used.

Results and Discussion

We first address the residential cases, comparing the solutions offered by the mothership to traditional built forms in terms of operational and embodied energy and embodied carbon. We then examine the retail and office use types in the same way, and finally the combination of

all use types, which is the overall purpose of the mothership concept.

Residential

The energy and embodied carbon results for the residential base cases, and the residential components of the mothership cases are shown in Figure 1 and Figure 2. Each of the scenarios is compared as a percentage reduction in energy use and emissions relative to the single detached home base case. One trend that can be seen is the decrease of energy use with increasing density. An exception to this is the high-rise buildings, due to energy use increasing as building height increases (Godoy-Shimizu et. al. 2018). The embodied carbon for each case also decreases with increasing density until the buildings are made with concrete where it sharply increases due to it being much more carbon and energy intensive to produce than wood.

Of the base cases, low rise apartments had the largest reductions in energy use and embodied carbon, 64% and 47% respectively. The PH cases with higher insulation levels had significant energy reductions at the cost of increased embodied carbon, except for low-rise apartments which saw a reduction. The residential components of the motherships saw high energy reductions, again at the cost of increased embodied carbon. The wood framed motherships saw slightly higher energy savings than the other motherships, as well as high reductions in embodied carbon of 80%.

The results also indicate that although significant reductions in energy use can be gained by super insulating buildings (even accounting for the higher embodied energy and carbon associated with the higher performance building envelopes), there are still further significant gains that can be achieved through higher density. Especially when that increased density is built with less embodied energy and carbon intensive building materials

Figure 1: Comparison of operational and embodied energy and change relative to the single detached home base case.

Figure 2: Comparison of embodied carbon and change relative to the single detached home base case.

Figure 3: Comparison of operational and embodied energy of each of the retail and office scenarios and the motherships. The percentage change for each base case is calculated relative to the retail or office case of that building type. The mothership cases were compared against the best performing retail and office base cases, RO1 PH WF and RO1 PH WF respectively.

Figure 4: A comparison of embodied carbon of each of the retail and office scenarios and the motherships. The percentage change for each base case is calculated relative to the retail or office case of that building type. The mothership cases were compared against the best performing retail and office base cases, RO1 PH WF and RO1 PH WF respectively.

Retail and Office

The energy intensity and embodied carbon results for the RO scenarios are shown in Figure 3 and Figure 4 respectively. Some of the building shapes such as expansive single storey spaces like RO 1 are not usually seen as office spaces. Likewise, in the local context, there are very few retail spaces that are multi-storey. However,

for consistency, all the use type cases were modelled with each building type, even though they may not be realistic. Each building use type is compared to the base case for that use type using a percentage difference. For example, the RO 3 office PH WF is compared to the RO 3 office base case, and RO 1 retail PH is compared to RO 1 retail. The retail and office components of the motherships are compared to the best performing retail and office base cases, that is, RO 1 retail for mothership retail spaces, and RC 3 office for mothership office spaces.

In each of the scenarios, the super insulated PH cases saw significant energy reductions. The PH WF scenarios saw similar energy reductions for RO spaces in addition to significant reductions in embodied carbon (84% average)

The best performing retail scenario was RO1 PH WF at 33,290 kWh/person (27% reduction) over the building's lifecycle. The operational energy use reduction is nearly identical to the PH case, however it substantially (77% reduction) out performs concrete in terms of embodied energy and emissions. The performance of the RO1 scenario was closely followed by the RO3 PH WF. The best performing office scenario was RO1 PH WF at 28,785 kWh/person (33% reduction) over the building's lifecycle and a 78% reduction in embodied carbon.

Combined Residential, Retail, and Office Comparison

The results for the residential and RO spaces were combined to come up with total energy use intensities and embodied carbon intensities for all the cases. These results can be seen in Figure 5 and Figure 6 for energy and carbon respectively. The plots show the operational energy use, embodied energy, and embodied carbon, as well as the percentage reduction relative to the single detached home use type combined with the best performing RO cases with to-code building envelopes. There are four main categories consisting of: base case with to-code RO, base case PH with RO PH, base case PH with RO PH WF, and mothership cases. The base case consists of the residential base cases, combined with the highest performing to-code retail and office space cases. Likewise, the base case PH consists of the residential base case PH combined with the best performing RO PH cases. The base case PH WF consists of residential base case PH combined with the best performing RO PH WF cases. Finally, the mothership cases are simply their combined individual residential spaces and retail and office space values.

In all the non-mothership cases, low rise apartments perform best due to their higher density, and their lower height enabling timber construction to save on embodied energy and carbon. They achieve energy reductions of 57% and 66% for the to-code case and the PH cases respectively and 35% reductions in carbon for base case and base case PH. The low-rise PH case with timber frame RO structures achieved a 50% reduction in embodied carbon.

Figure 5: Compares operational and embodied energy of each scenario to the combined results for single detached home with the highest performing to-code retail and office cases.

Figure 6: Comparison of embodied carbon to the combined results for single detached home with the highest performing to-code retail and office cases.

Medium-rise apartments show a similar, although lower energy reduction than low rise apartments, however building with concrete makes their embodied energy and carbon much higher. High-rise apartments do not perform as well as lower density apartments in terms of energy use or embodied carbon. The timber framed mothership cases appeared to be the best cases. Their energy use being slightly higher than the other mothership cases, but very large improvements in embodied energy and carbon, totalling 23% and 76% respectively, when compared to the same mothership cases built with concrete. Compared to the single detached house base case these reductions are 71% and 78% for energy and embodied carbon respectively.

An interesting comparison is that of the mothership performance to low-rise apartments. The motherships outperform all the base cases in terms of energy use, and the WF motherships outperformed in both energy and carbon. However, low-rise PH and PH WF apartments perform similarly to motherships, although less so in terms of embodied carbon, they still outperform all the concrete motherships.

Conceptually speaking there isn't many obvious things that can be done to further reduce the energy use and emissions of a group of buildings as cost effectively as making density higher and reducing surface area, and super insulating it as much as is realistically possible, without sacrificing other aspects such as natural light. A

building could be designed with an even smaller surface area to volume ratio, but at some point, the natural light availability inside the structure will suffer, and increasing glazing to compensate often introduces other problems such as increased losses and overheating in summer.

This leads to the mixed-use aspect of the mothership design. It is an aspect that does not increase building costs by a large factor, but it can have a large effect in terms of overall energy use and emissions of the residents by reducing the number of personal vehicle trips. The effect could be compounded by having a transportation hub that would reduce the vehicle trips of the surrounding neighbourhood as well as the mothership residents.

Another advantage is having an advanced district energy system. Not only are these systems efficient and allow for different types of renewable generation and storage technologies to be used, it can also be optimized to share energy between the retail and office spaces, and the residential areas (Entchev et al. 2013). One example could be the extracted heat from cooling a server bank could be used to heat hot water for the residents.

Future Work

As mentioned in the method section, a major limitation of this work was not being able to have an automatic way of running the UMI simulations in grasshopper. Future work will include potentially developing a work around for this. The advantage of being able to run simulations automatically is that there are optimizer components in grasshopper that will vary the parameters based on their algorithms to optimize the design geometry for some parameter, the obvious one being energy use, but it could be any other calculated value.

It is important that a potential solution such as the Mothership will be able to perform well in different locations and climates. Therefore, a climate analysis will be performed, using different locations and climates to examine the effect on energy demand. Additionally, a climate change resilience study will be performed using weather files for future climate projections for these locations. This will show whether a Mothership style design is more resilient to a changing climate than traditional building types.

According to Natural Resources Canada (2018b) and Natural Resources Canada (2018a), approximately 16% of total energy use and 14% of produced emissions are associated with residential and commercial building space heating in Canada. Transportation accounts for 30% of total energy use, and 38% of emissions. Energy use of buildings can be reduced drastically through high performance building envelopes and using renewable sources of energy to provide the required heating and hot water through heat pumps. As this occurs, the proportion of emissions and energy use due to transportation becomes more significant than it already is. As a result, the conscious design of the built environment to minimize the need for personal vehicle trips and providing emissions free public transportation has the potential to yield huge reductions. Future work will attempt to quantify the effect of reducing the number of personal

vehicle trips and using public transit that the higher density mixed use of the mothership can provide.

Opportunities for energy sharing between the different use types exist and deserve to be explored. To do this, an energy system optimization tool called the Energy Hub (EHub) (Evins et al. 2014) will be used.

Conclusion

A potential holistic solution to urban sprawl called the Mothership was modelled and compared to more traditional building archetypes. Building operational energy use as well as the embodied energy and emissions were the metrics used in the comparison. The motherships as well as super insulated versions of the base cases were compared to the single detached houses base case. Of all the mothership cases examined, the timber framed cases performed best, with similar energy use reductions to other motherships, but much lower embodied energy and carbon than the other mothership cases. Timber framed motherships showed reductions of 71%, 73%, and 74% of operational energy, embodied energy and embodied carbon respectively. The super insulated low-rise apartment case also performed similarly to the timber framed motherships, however they wouldn't necessarily benefit from the effects of mixed use as the mothership does. It is also important to note that the energy reductions associated with higher density taper off with increased height, as the higher the building is the more energy it uses. In the end, building energy use and emissions are but a part of the overall consumption of the built environment, and it is important to consider transportation and proximity of amenities in addition to buildings since they become more significant as building effects are reduced.

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