Flexible Spaces: Value Creation Through Robotics in Multifamily Real Estate
by

Leonel Felipe Fierro Peñuela

B.A., Architecture, 2010
B.A., Economics, 2011

Universidad de los Andes, Colombia

Submitted to the Program in Real Estate Development in Conjunction with the Center for Real Estate in Partial Fulfillment of the Requirements for the Degree of Master of Science in Real Estate Development

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Signature of Author Signature redacted
Center for Real Estate
January 8, 2016

Certified by Signature redacted
Professor Albert Saiz
Daniel Rose Associate Professor of Urban Economics and Real Estate, Department of Urban Studies and Center for Real Estate

Accepted by Signature redacted
Professor Albert Saiz
Daniel Rose Associate Professor of Urban Economics and Real Estate, Department of Urban Studies and Center for Real Estate

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ABSTRACT

Current demographic patterns suggest that the future will offer denser and more crowded cities globally, leading to smaller and more expensive apartments for those who wish to live in urban environments. The viability of robotic furniture systems to enhance the utility of smaller residential units could alter the landscape of real estate development in urban environments. This thesis examines the feasibility and value generated through robotic systems in real estate.

Thesis Supervisor: Albert Saiz
Title: Daniel Rose Associate Professor of Urban Economics and Real Estate, Department of Urban Studies and Center for Real Estate

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Finally to my parents who let me dream and reach this far, and to Juan and Mateo who showed me a different way to venture in life, los adoro.

Now we begin…

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1. Introduction

Experts have been recently debating whether Millennials prefer to live in "vibrant urban centers" or whether their observed predilection for city dwelling is just a delayed transition to the suburban American dream. The issue is far from settled. Driving this discussion is the increased demand for multifamily residential units in urban centers. As former New York Mayor Michael Bloomberg points out, despite increased demand, "New York City has 1.8 million one- and two-person households, but only one million studios and one-bedrooms."[1] According to CBRE Group, factors such as the deindustrialization of central cities, changing lifestyle preferences and shifting demographics have contributed to renewed interests in urban living. Of these factors, demographic changes have a special relevance to the changing demands in the housing market; between 1960 and 2010, the overall share of married Americans declined from 72% to 51%, accompanied by a decrease in the average household size from 3.33 to 2.58 during the same period.[2]

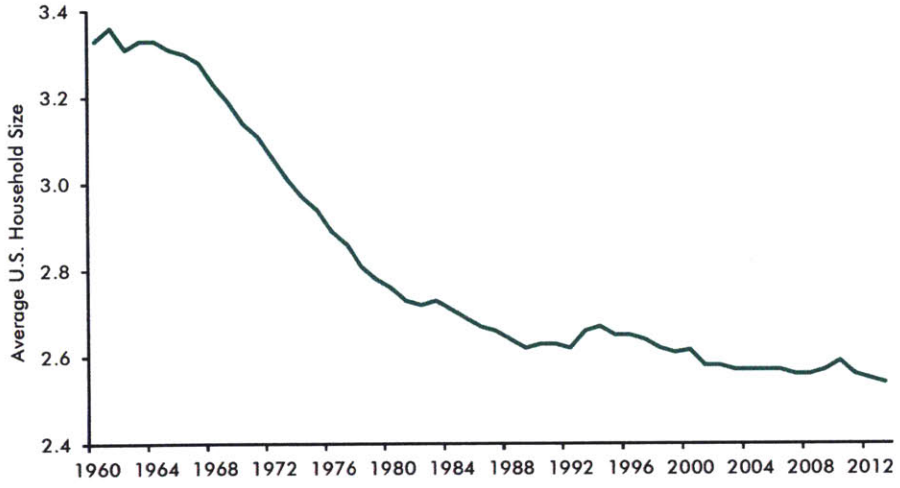

Figure 1 US decline in average household size [2]

The market supply has not been able to adjust to changes in demand, resulting in significant increases in apartment rental rates and real estate prices in major cities like New York, San Francisco, Washington DC and Boston. Cities like San Francisco have experienced vast inflows of young, entrepreneurial professionals, who have been at the center of the city's economic growth and transformation for decades. The success of the technology industry has resulted in price spikes, beginning to price out the creative class that feeds this economical and cultural growth.[3]

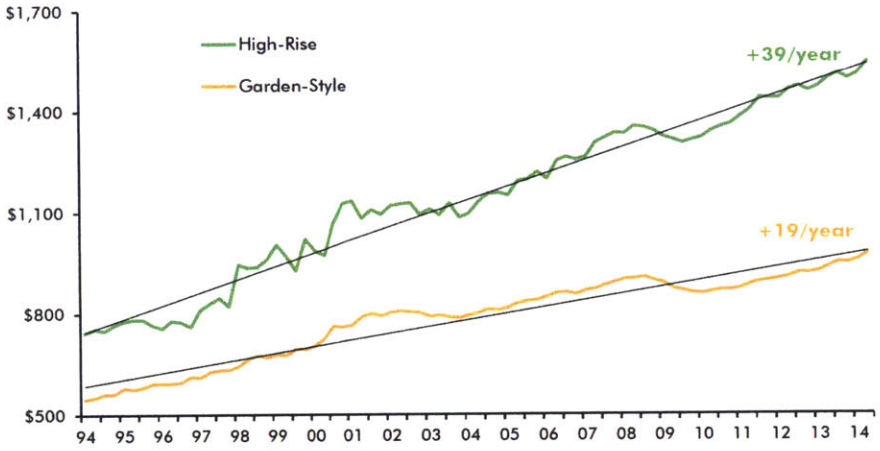

Figure 2 High rises rents growth above suburban garden apartments [2]

In an attempt to reduce upward pressure on rents, a number of leading cities have been working on different strategies to increase the supply of rentable units. For example, San Francisco is reviewing its zoning policies to allow higher density development,[4] Seattle and Portland have pioneered the creation of accessory dwelling units on Single Family parcels, and Boston is promoting the development of the "innovation" district on the seaport to foster residential affordability and economic growth. One complementary strategy would be to expand the housing supply by allowing higher density through smaller units and less parking instead of additional height in new developments. By building smaller, un-parked units, these cities allow their

respective real estate development communities to create an affordable product without extraneous and expensive features that drive up rents.

One response to these issues is a new real estate product that has been defined as the micro unit: "a small studio apartment typically less than 350 square feet, with fully functioning and accessibility compliant kitchen and bathroom."[5] Cities have been actively fostering the development of this typology: San Francisco allows 220 square foot apartment units,[6] while the Bloomberg administration dropped the limit in New York City from 400 to 350 square feet for the highly publicized "Living Small NYC" project. "Living Small NYC" is a proof-of-concept development that uses prefabricated modular construction and leases some of its furnished units with space efficiency furniture such as murphy beds and creative storage.[7]

Figure 3 Carmel Place, winner of adAPT NYC Competition [8]

Despite these examples of flexible furniture gaining popularity among new micro unit developments, the impact of the resulting "flexibility" on a property's income and operations has not been properly studied. While the industry is still figuring out how to price these features in the units, technology is moving a step further. At the MIT Media Lab, the Changing Places group has been working on initiatives such as "CityHOME: 200 SQ FT." The initiative aims to develop disentangled robotic furniture systems to improve the usability of space. The implementation of "furniture with superpowers" (as robotic furniture is called by the research

team) promises to deliver effortless flexibility that will finally allow users to maximize space in their apartments.

It appears that technology may finally present a solution to issues of density and quality of life in affordable urban living. This thesis evaluates how Robotic furniture can close the gap between technology and the real estate industry. What are the principles and uses of this technology? What are the spatial and utilitarian gains that robotic furniture allows? What is the added value to a commercial property that implements a flexible space system? These are the core questions that this document seeks to answer.

2. State of the Art

Architecture has evolved in such a way that different uses (sleeping, cooking, studying, bathing, etc.) require dedicated spaces. Consequently, a significant amount of space in apartments remains completely unused most (if not all) of the time. What if we could transform this unused space? Architects and designers have been dreaming up space economization solutions for decades, and futurists and artists have also contributed insights for the flexible apartment of the future.

Figure 4 Korben Dallas apartment in 2263, The Fifth Element (1997) [9]

Transformable living spaces have the potential to revolutionize the lives of their users. Living in a smaller footprint would allow societies to build denser cities, where the use of natural resources, infrastructure and transit would be more efficient and productive. Additionally, this could be a vital strategy to maintain people close enough to interact with each other, as this human interaction oils the "machine of creativity" that makes a city thrive.[3]

It is not easy to choose the most relevant past examples of flexible furniture. Since Gerrit Rietveld designed Schröder house in 1924, in which moving panels allowed users to change the configuration of space depending on its use, there have been hundreds of attempts to come up

with solutions for transformable spaces. With the help of the Internet, several flexible design proposals have become viral, reaching millions of people and demonstrating the public's interest in these types of solutions. The following examples were chosen due to the attention they received when presented, as well as their importance as representative examples among different approaches used to confront the challenge of apartment flexibility.

Domestic Transformer (2007)

The New York Times first featured Gary Cheng´s apartment in 2009 with the title ¨24 Rooms Tucked Into One.¨ In the article the architect described the situation of people living in Hong Kong studios: "People feel trapped," he said. "We have to find ways to live together in very small spaces." His innovative proposal became very popular for the number of different strategies it proposed and the resulting unique spaces it achieved. However, his example is at the top of a long list of designs that prototyped solutions for effective space flexibility, yet never reached mass production.

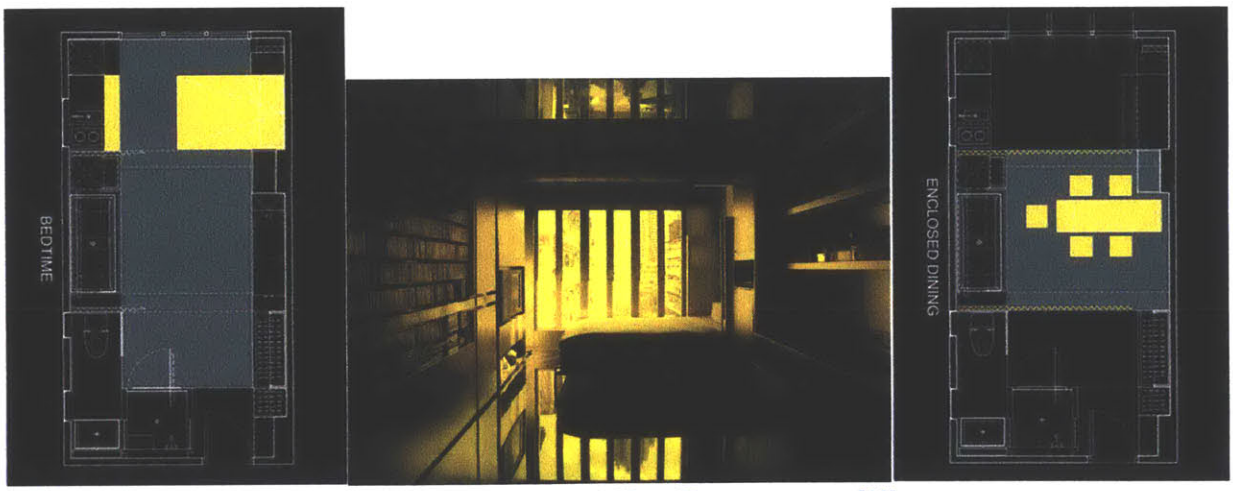

Figure 5 Two variation and photograph of Gary Cheng's Hong Kong apartment [10]

Life edited apartment (2012)

Graham Hill's apartment in New York City was presented in a YouTube video called ¨6 rooms into 1: morphing apartment packs 1100 sq ft into 420¨ and has more than 5.2 million views on YouTube. Hill's apartment was different from previous approaches, as he used commercially available furniture to achieve space flexibility, showing that flexibility could be implemented in regular apartments. Since then, Murphy beds and folding tables have started to be used in commercial real estate. Despite its success, the "Life Edited", Graham's company, manual furniture approach still lacks the effortless component of truly flexible space; furniture like murphy beds are convenient for sporadic use but become burdensome for daily users. Price is the other factor that remains a major barrier to mass use; since the apartment was presented in 2011, only high-end projects have experimented with this approach and furniture prices have not dropped.[11]

Figure 6 Life Edited apartment, SOHO NYC [12]

Changing Places, Media Lab MIT

The MIT Media lab is famous for its unconventional approach to problem solving. The Changing Places Group is the Media Lab team that works to envision the future of cities. Their initiatives include the development of shared vehicles and augmented reality in urban planning. One

research area at Changing Places has been to develop robotic furniture, and their 200 SF prototype video has over 1.3 million views on YouTube. This prototype presented two major innovations: first, the system used mechanical transformation of space to make all transformations effortless; second, the system integrated computing capabilities that allowed the furniture to be Internet-connected and even able to be customized through apps, allowing for multiple user interfaces.

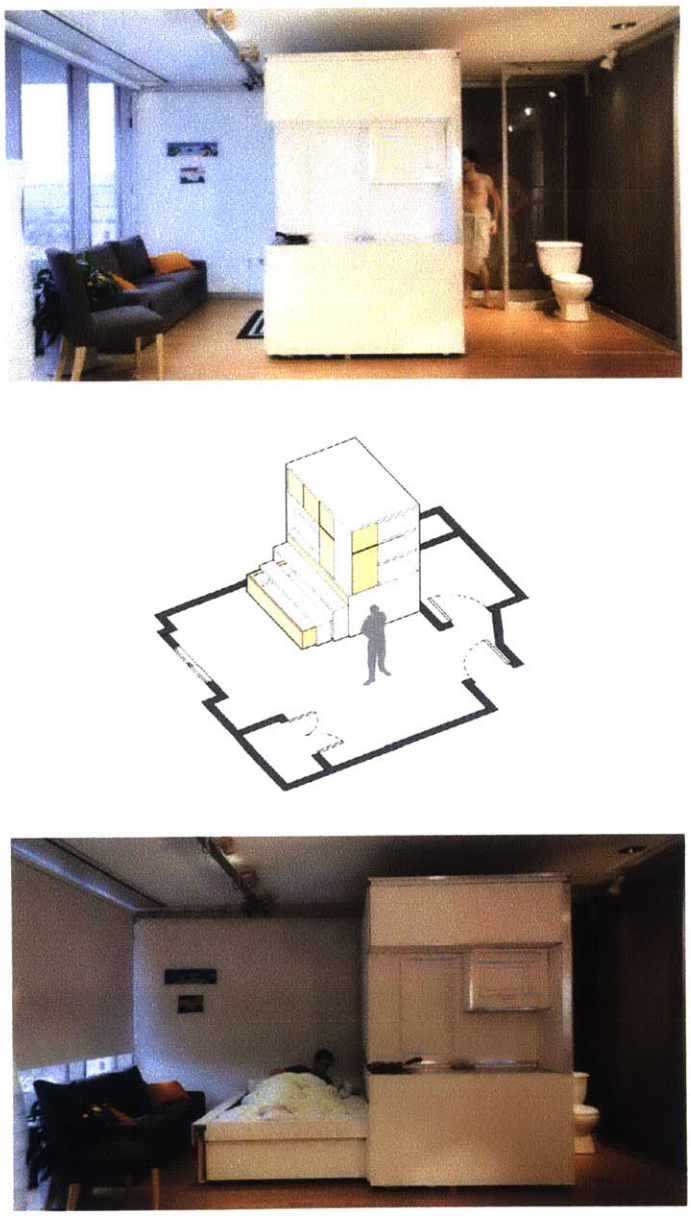

Figure 7 CityHome 200 SF prototype [13]

Even though each of the previous examples of flexible furniture drew attention from the public, none has been widely implemented in commercial real estate. If flexible furniture is the future of residential properties, the next "solution," its implementation should be able to merge the advantages of each of those proposals:

- Residential space is not standardized; therefore, flexible furniture must be adaptable to individual situations (Gary Cheng's apartment).
- Multifamily owners are hesitant to adopt "one off" solutions, so commercial availability of technology is critical for adoption (Life Edited).
- Daily use of flexible furniture demands effortless transformation; mechanical conversion and even automation can solve this issue (MIT Changing Places).

Currently, there are initiatives working to overcome the challenges of flexible homes. "Yo!Home" and Morphlab, a Changing Places Spin-off Company, are among them. Morphlab's proposed approach can be found in Larrea's (2015) thesis, "ARkits: Architectural Robotic Kits," which presents a method that meets the abovementioned requirements. ARkits is "a kit of parts that compartmentalizes the complexity of robotics – mechanics, electronics and software – in order to empower architects, designers and "space makers" in general to create endless product possibilities based on Architectural Robotics core principles." [13]

An ecosystem of robotic building blocks will empower architects and designers, who are traditionally unfamiliar with electronics and mechanics, to design spaces that change throughout

the day. ARkits will give the architectural elements like regular furniture motors, mechanics and electronics to coordinate movement with simple components.

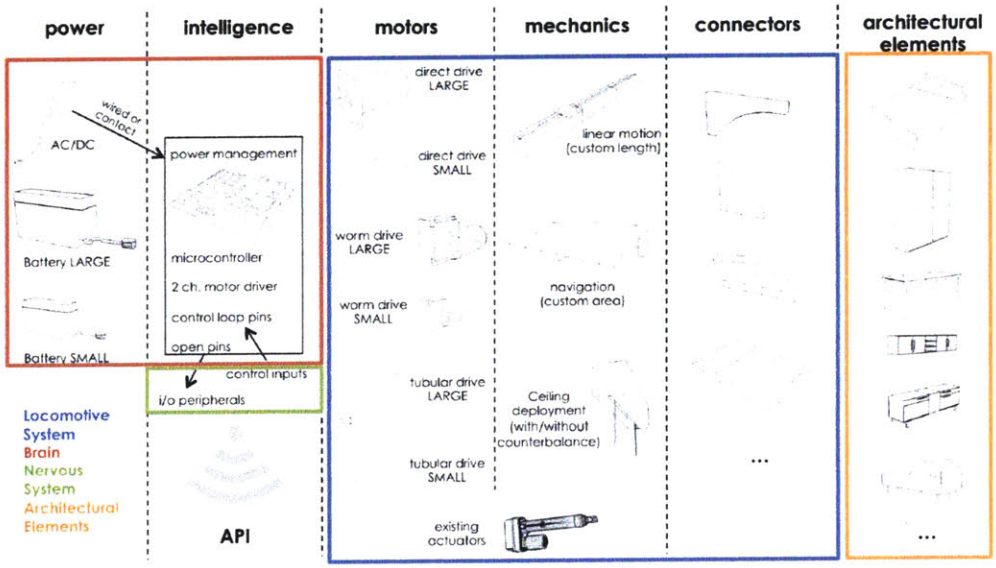

Figure 8 ARkits proposed ecosystem [13]

3. Technology Analysis, Component Costs and Learning Curve

Flexible use of space has the potential to transform the relationship between users and the spaces they inhabit. Rooms that transform throughout the day extend the interaction between users and their spaces, while maximizing the utility derived from their homes. Despite such a powerful concept, space flexibility as explained in the previous section has never been implemented on a mass scale, and until now its transition to commercial real estate was not expected.

Technology that has made the transition to mass usage usually follows a path in which businesses are the early adopters. Computers and 3D printers are good examples of this pattern. New technology is usually expensive, and businesses are frequently able to get higher returns than individuals are. During the early years of any new technology, there is a steep learning curve to improve efficiency, lower costs, and add new features that increase its appeal to the regular consumer.

Larrea (2015) claims that flexible furniture has not been able to permeate the built environment due to the "one off" solutions approach, which is unable to fit a diverse built environment. ARkits proposes a solution in which designers can use a kit of single elements (building blocks) in any space to achieve any transformation. Among the possible transformations, translation[1] is the easiest to implement as a stand-alone system. This factor is a determinant of attractiveness of robotic furniture for commercial real estate.

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[1] Translation: Moving an element along an horizontal or vertical axis attached to a solid surface

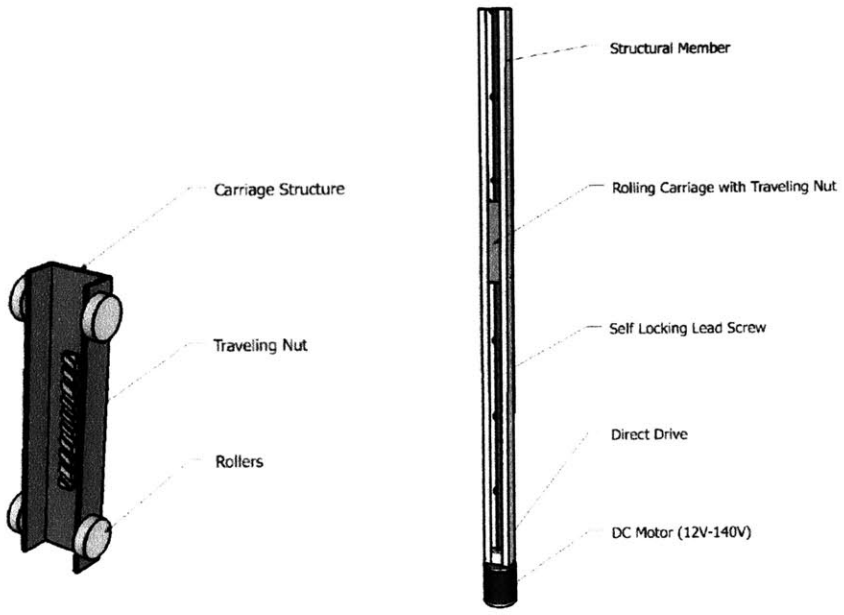

Figure 9 Mechanic system for horizontal or vertical furniture translations [13]

Translation systems allow for the development of furniture such as multifunctional cabinets, moving wall drop-off beds, and tables with simple mechatronics (figure 9). However, translation systems are restricted in that they can only be attached to solid surfaces like walls, ceilings, and floors. This apparent limitation actually reduces the intricacy of the systems, clustering the complexity on a fixed surface and allowing for a stand-alone setting suitable for renovation.

True stand-alone systems require installation without any additional construction costs beyond the system itself. If the only cost for developers is the price of the robotic furniture, then the concept of a technological learning curve[2] becomes critical in the adoption of this technology. Famous examples of this concept are Moore's law for integrated circuits and Swanson's law for

[2] Cost of production of new products tends to decrease over time due to efficiency learning, competition and market specialization.

photovoltaic panels, where prices have fallen from $76.67 per watt in 1977 to $0.36 per watt in 2014.

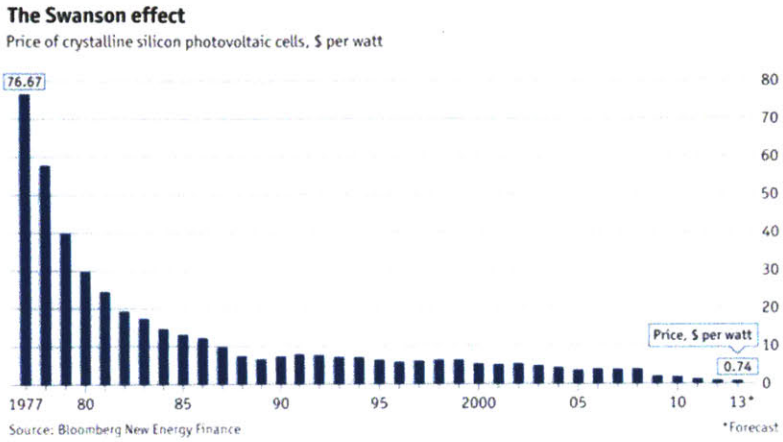

Figure 10 Price per watt evolution [14]

The price of robotic furniture can be expected to decline over time. However, it is unlikely to follow a similar price trend to that of microchips or solar panels given that a big portion of the cost of the robotic furniture is in the architectural components (furniture such as beds and cabinets). The learning curve for regular furniture is already advanced, limiting its potential for cost reduction. Nevertheless, cost reduction via economies of scale will be reachable as long as the mechanical and computational components are subject to increasing efficiency. The type of furniture to be used will also significantly influence price and determine the potential for affordable versions.

Modularity and customization are important factors in achieving widespread acceptance of robotic furniture. Nevertheless, to achieve the vision of customized robotic units the built environment must adopt first simpler versions in existing units. Morphlab seems to be aware of this dynamic; they are testing alpha units in Boston at the time that this thesis is being written.

The alpha unit that we will call S1 uses a translation system and functions as a bedroom, study, walk-in closet and living area for studios and micro units.

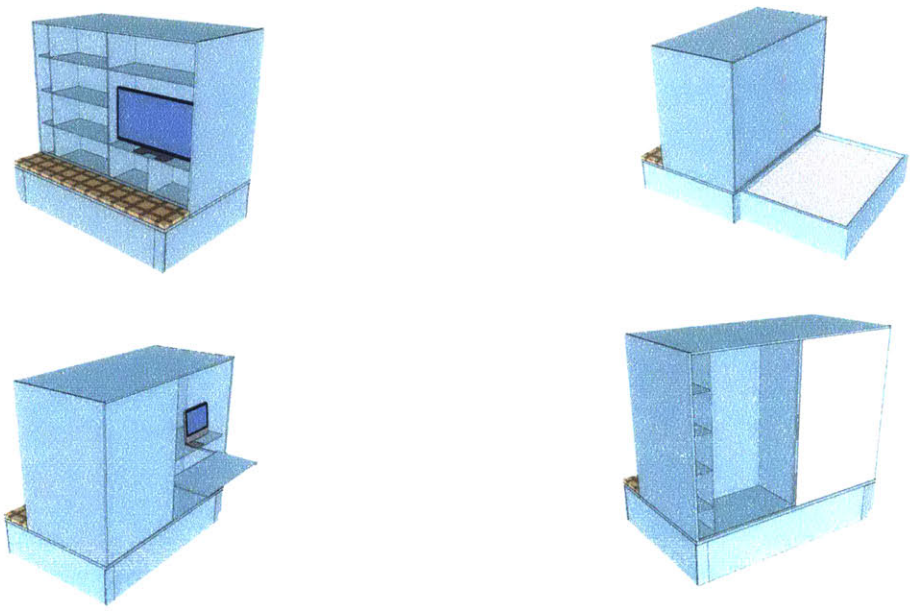

Figure 11 "S1" Morphlab alpha robotic furniture systems, Morphlab courtesy

Living area/ Bedroom / Study room / Walk-in closet transformations

4. Architectural Analysis of Spatial Impact of Robotics

As humans we have an intrinsically complex relationship with space. The perceived value of an apartment depends on individual preferences, taking into account factors such as size, design, age, ceiling height, views, floor, finishes, light, location and many others. Developing a system to qualify and quantify all the different attributes of an apartment is a complex task that is beyond the scope of this document. However, given the objective of robotic furniture to maximize the usability of space, a good variable to measure the impact on utility is the increase in usable area.

Robotic furniture applications and flexibility inside a unit have numerous possibilities. Projects such as the Changing Places "Chassis" propose a future of housing in which standardized construction is customized by the use of several robotic furniture systems. However, that broad range makes it hard to assess the potential impact of the technology. For the purpose of simplicity, this analysis will be developed with two major constraints:

- The evaluation will assume that this technology has a learning curve that makes the cost decrease over time while adding new functionalities. Compared to the fully implemented technology, the first systems would be relatively expensive. This would limit the number of systems per unit, which would impact the apartment typology that suits robotic furniture, maximizing the marginal impact for the user. As shown in the table below, restricting robotic furniture systems to one system per unit causes small apartments, such as studios and micro units, to experience a larger percentage increase in usability.

Figure 12 *Percentage of perceived area gain by implementing robotic furniture systems*

Area gain/unit size	300 SF	400 SF	500 SF	600 SF
50 SF	17%	13%	10%	8%
60 SF	20%	15%	12%	10%
80 SF	27%	20%	16%	13%

- The analysis contemplates a scenario in which robotic furniture will become the standard in the development of residential buildings. However, the main focus of this analysis is to test the conditions that will drive the technology's rapid adoption in the wider marketplace. Therefore it makes sense to limit robotic furniture systems to arrangements that are capable of working as standalone systems in existing buildings without requiring extensive retrofitting.

The following image simulates the use of the S1 furniture in an "innovation" unit at Boston's seaport (the original floor plan has since been modified, eliminating the closet area to increase the S1 effect). S1 transforms into bedroom, walk-in closet, extra living space, and study area to show the iteration of different functionalities within a single system. Nevertheless, this methodology could also be used with any other arrangement of flexible furniture.

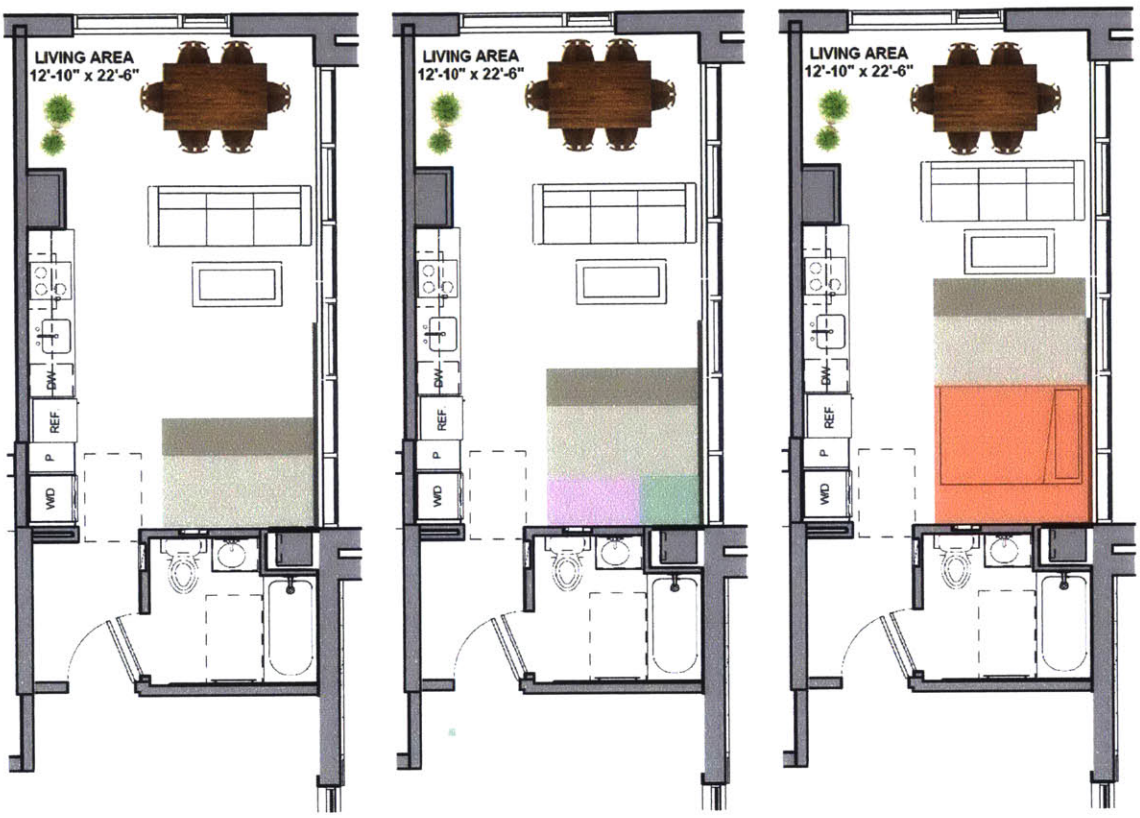

Figure 13 S1 transformation in a 410 square foot studio

Living room/ walking closet & study room/ bedroom transformations

From right to left, the first image shows the living configuration of the studio in which the bedroom, walk-in closet and study room are hidden. The area of this studio is 410 square feet (SF), which can be used entirely for living space in this configuration. The second image shows the first movement of S1. The increased area is calculated as the highlighted "circulation area," since the storage area is being used even when the system is closed. The "new" area for the walk-in closet is 11 SF (purple area) and study room 10 SF (green area). The third image shows the increase in effective area due to the bedroom (red area) generating an increase in perceived area of 50 SF, totaling 71 SF of usable area in the studio, a gain of 17% over the initial area.

The concept of usable area is being proposed here as a proxy for the increased utility of the user. However, this percentage should be adjusted downwards due to factors such as inability to use "new" areas simultaneously, as well as the time of transformation for each use. The utility reduction factor will be unknown until market usage data is available, but it is conservative to assume that the increase in percentage of usable area can be a benchmark ceiling for the potential increase in rents.

On the contrary, this approach only takes into account the increased utility due to area. Morphlab systems propose allowing users to monitor activities in their homes, and personalize the performance of the furniture in different scenarios through "apps." The effect of such features on the user's utility is unclear and is thus excluded from the present analysis.

5. Investment Analysis on Robotics System DCF Approach

Commercial real estate assets are valuated under the same principles as other businesses: the value is determined by forecasted cash flows of the property, discounted at a rate that takes into account the risk associated with the opportunity. Among the different product types available in commercial real estate, urban multifamily properties are considered to have a lower risk than other product types. Artificial barriers to entry such as supply constraints (in the form of onerous regulations and prohibitive land use codes), and having multiple tenants for a given property are key factors that lower the volatility of the income stream associated with residential properties.

The lower risk associated with multifamily properties is translated into a lower capitalization rate (or "cap rate") for this type of property, a measure of yield common in the industry. This means that residential buildings are valued at a higher price though they have the same projected cash flow as other property types, a characteristic that should make developers and real estate investors more interested in upgrading the income of the property. This is not common, however, since any process that requires construction is usually too expensive and time consuming to be taken into account.

Acceptance of new technologies in real estate must make economic sense, meaning that the cost of adopting a new technology should be offset by its expected return. Therefore, value creation can happen through different channels. The following technological advancements describe patterns relevant to the analysis of robotic furniture:

- Technology adoption to increase efficiency:
    - Reinforced Concrete: This technology combined with the industrial production of steel allowed construction to revolutionize itself in the 19th century. Reinforced concrete allowed higher structural capabilities while reducing requirements for materials and labor. [15]

    - Construction Machinery: The usage of construction machinery is a good example of how economic conditions determine whether or not technology will be adopted. While the usage of machinery in construction is extensive in the developed world due to the resulting efficiencies in time and labor, it is common to find lower adoption rates of these technologies in developing countries due to lower labor costs. Low cost of labor makes it more efficient to increase the number of construction workers than to invest in machinery.

- Technology adoption to meet demand preferences:
    - Green Buildings: It could be argued that green building technologies increase construction costs for developers while producing only a marginal impact in revenue. But Chegut (2013) shows how London developers have achieved supernormal profits[3] after the incorporation of green technologies, calculating 21% rent premiums over traditional office buildings. The reason being that

[3] Supernormal profits are achieved when a innovation allows investors to realize higher returns adjusted for the risk level.

demand for office space has favored green buildings, allowing this type of property to charge higher rents and have lower vacancy rates. [16]

- Elevators: The modern elevator was invented by the end of the 19th century. By then, construction technology was able to build higher buildings, but stairs reduced the desirability of higher floors. The introduction of elevators allowed effortless vertical transportation, which unlocked the value of higher floors in terms of views and isolation from street levels. [17]

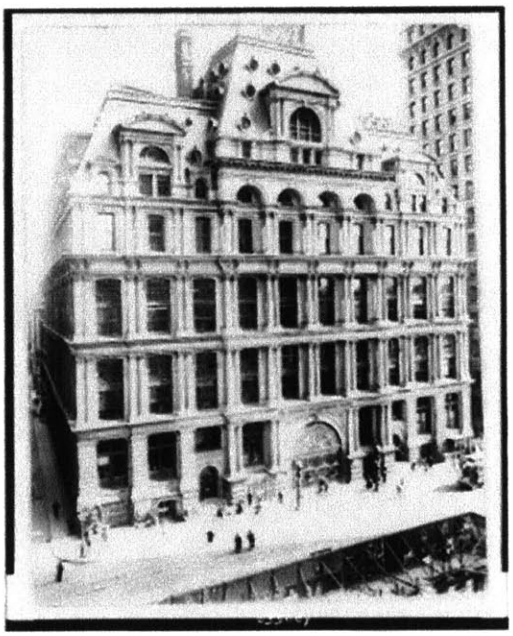

Figure 14 Equitable life Assurance Building, first building with passenger elevator [18]

5.1. Residential Usability Premiums

Whenever there is the need to choose an introductory price to market a new product, comparable analysis is the most used method. In the case of robotic furniture, finding products that offer similar experiences and benefits can be challenging given its innovative features. However, some amenities offered in apartment buildings can benchmark the price range that robotic furniture premiums could charge in the rental market.

A hedonics model regression is an accurate methodology to use to uncover the premiums of these features. Unfortunately, public data on effective rents and amenities is not available, and a regression using handpicked listed rents could lead to incorrect conclusions.

The following examples show rent premiums in handpicked equivalents, with the estimated premium values indicative of the amenity value. However, with the limited data it is unreasonable to extrapolate these examples to a general situation, though they can help in understanding the fundamentals of residential amenities premiums.

- **Furnished and unfurnished units:** Furnished apartments charge 15% to 40% more than equivalent unfurnished units, depending on the quality of the furnishing. The common explanation that higher rents are due to increased convenience is insufficient. Furnished apartments are marketed for shorter lease periods, increasing vacancies and using the premium as a way to recover lost income. For example, a studio costing $2000 USD in monthly rent would charge a furnishing premium in the range of $400 to $800 USD.

- **Murphy beds and unfurnished units:** Since micro units already have shorter leasing periods and lower releasing rates, furnished units with flexible furniture like murphy beds have become popular as a way to reduce the friction of buying new furniture for new tenants, while diminishing the disadvantages of small living spaces. At Carmel Place[4] (figure 1) in New York, "a furnished 355-square-foot apartment on the second floor is listed at $2,910, while an unfurnished 360-square foot unit on the same floor is listed for $2,750 — a $160-a-month discount." [19]

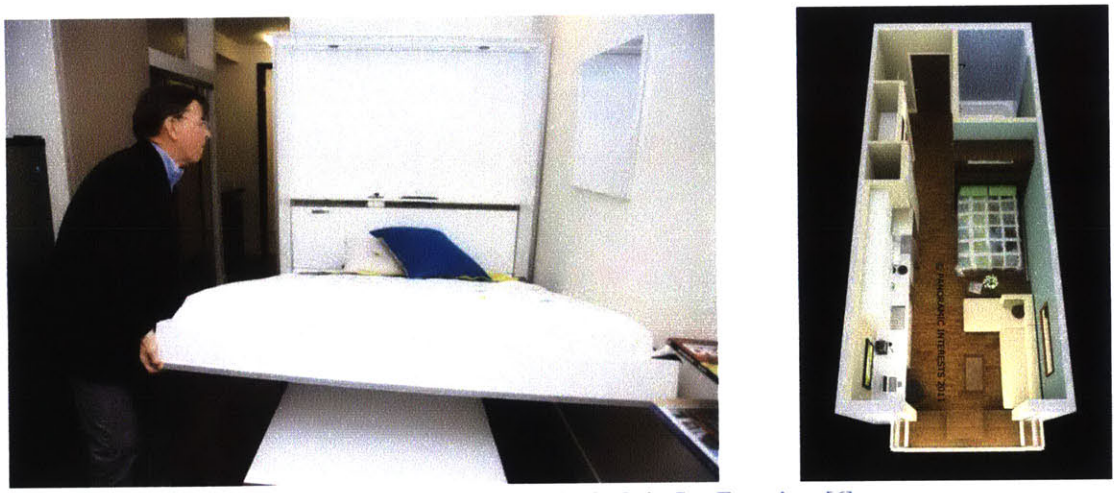

Figure 15 Smart Space's 285 square-foot apartments with murphy beds in San Francisco [6]

- **Storage service:** As apartments have become smaller, a common complaint is the lack of storage space. Storage units are offered as an additional service in some buildings, at different price ranges depending on the area. Cubiq is a Boston startup proposing to create storage space on demand. Their business model provides delivery and pickup of storage cubes while keeping an inventory of the content online. The price for the storage

[4] As mentioned in the introduction, Carmel Place was the winner of the adAPT competition for micro units in NYC

of a 2.4 cubic foot cube is around $7 USD per month, including limited pickups and returns. The volume of storage in the S1 is equivalent to 50 Cubiq boxes; a rough (and unfair) comparison will valuate the storage generated by the unit at over $300 dollars. [20][21]

Even though none of the previous examples are directly comparable to robotic furniture, the prices charged in the market for those amenities gives a sense of the range within which rent premiums for robotic furniture might fall. Morphlab has surveyed realtors who have visited the alpha units to assess the premium for the S1 system. Survey results show a monthly rent premium for a studio in Boston of around $375 USD, these numbers are consistent with the previous examples.

5.2. Financial Impact of Robotic Furniture

There is no such thing as an "average building" to forecast the impact of the introduction of robotic furniture. Two similar buildings located close to each other geographically, for example in New York and Philadelphia, will have big differences in their economics, construction costs, rental prices and demand preferences. Nevertheless, the financial cash flow analysis of any real estate property should be modeled in the same way, allowing for the development of a single work frame to evaluate robotic furniture adoption.

Operating (all years):		
Potential gross income (PGI) = (Rent/SF) × (Rentable SF) =		PGI
– Vacancy allowance = – (Vacancy rate) × (PGI) =	–	V
+ Other Income (e.g., parking, laundry) =	+	OI
– Operating expenses* =	–	OE*
Net operating income =		NOI
– Capital improvement expenditures** =	–	CI**
Property-before-tax cash flow =		PBTCF
Plus reversion (only last year and when partial sales occur):		
Property value at time of resale =		V
– Selling expenses (e.g., brokers' fees) =	–	SE
Property-before-tax cash flow =		PBTCF

Figure 16 Typical Line Items in a Proforma for Income Property [22]

To further simplify the impact of robotic furniture in a generic real estate project, the cash flows generated by the system can be analyzed independently and then added back into the general cash flow. The net present value (NPV) of these cash flows at the target weighted average cost of capital rate (WACC) will determine the economic viability of the inclusion of robotic furniture in the project. A positive NPV value will mean that the addition of robotic furniture enhances the financial performance of the project.

The early development stage of the technology restricts the accuracy of the financial analysis; therefore most of the cash flows cannot be analyzed from a historic perspective. To overcome this limitation, the present evaluation builds a base scenario to then test the critical assumptions through a sensitivity analysis.

5.2.1. Base Assumptions

Even though the present analysis is a theoretical exercise, forecasted assumptions mimic the expected adoption path of robotic furniture. This analysis assumes stabilized properties as first

adopters, excluding additional construction costs and savings. We also assume high rise properties located in major cities with limited supply and high demand. The next table summarizes the main assumptions, with the particular analysis below:

Figure 17 financial assumptions summary table

System economic parameters		Developer economic parameters	
Initial Cost	$20,000	**Cost of equity**	21%
Target cost	$10,000	**Cost of Debt**	7%
Years to achieve target	10 years	**Leverage**	60%
Annual maintenance	$300	**WACC**	12.6%
Major maintenance	$3,000	**Hold period**	10 years
Major maint. frequency	5 years	**Inflation**	2%
System lifetime	10 years	**Rent Premium**	$220
		Reversion Cap Rate	6%

- **Analysis Period:** 10 years is a common period to evaluate the acquisition and performance of a property in the industry. It is also an adequate time frame for the technology to achieve the target price.

- **System cost:** since there is no commercial offering at this time, the present valuation assumes a $20,000 USD unit cost per system based on the expected price of Morphlab's current beta units (S1 functionality). The other major assumption is that each system will have a target price of just $10,000 USD in 10 years. Despite the fact that this analysis explicitly excludes the effect on construction, the next table

shows the impact of including robotic systems on construction costs in relevant markets in order to test the assumptions against economic reality.

Figure 18 robotic furniture effects in construction cost

	Test Building	New York	Washington	Boston	San Francisco
Cost/SF	**$340**	380	280	336	353
Ave unit size	**410**	478	450	434	485
Building efficiency	**75%**	75%	75%	75%	75%
gross area/unit	**547**	638	600	578	646
$ System cost/Unit	**$20,000**	$20,000	$20,000	$20,000	$20,000
$ System cost/gross area	**$37**	$31	$33	$35	$31
High rise cost w/ system	**$377**	$411.36	$313.05	$370.87	$384.10
% Cost increase	**10.8%**	8.3%	11.9%	10.3%	8.8%

Comparing the assumptions parameters with the market data, it can be determined that the impact on real properties is in the same range as these assumptions. The difference in the average studio size is consistent with an expected larger impact of robotic furniture in smaller units, and the assumption that micro units will be the first adopters.

- **Additional Rent Income:** Using existing real estate premiums and Morphlab's reported survey as a reference; a monthly premium of $220 USD seems like a good base line. The following table shows the assumptions in relation with market data in target areas.

Figure 19 robotic furniture effect on rental markets

	Test Building	New York	Washington	Boston	San Francisco
Studio median Rent	**$2,600**	2840	1950	2145	2598
Studio median Rent/SF	**$6.34**	$5.94	$4.33	$4.95	$5.36
Rent premium	**$220**	$220	$220	$220	$220
Premium/SF	**$0.54**	$0.46	$0.49	$0.51	$0.45
% System to median rent	**8.5%**	7.7%	11.3%	10.3%	8.5%
System area gains (Usable SF)	**71**	71	71	71	71
System area gains	**17.3%**	14.8%	15.8%	16.4%	14.7%
Theoretical Max rent premium	**$450**	$422	$308	$351	$381
Usable vs. real discount	**51%**	48%	28%	37%	42%
Theoretical usable Area	**481**	549	521	505	556
Theoretical rent/SF	**$5.86**	$5.57	$4.17	$4.69	$5.07
Theoretical renter discount	**8.16%**	6.59%	4.04%	5.54%	5.70%
Theoretical renter discount	**$230**	$202	$88	$131	$161

The apparent disparity between the assumptions and the market data shown in figure 13 is explained by the fact that the average rent variable includes properties in different conditions, while the assumption for initial target properties for robotic furniture is that they are recently completed or renovated. These properties charge rents above the average on each market.

Nevertheless, the required premiums for robotic furniture corroborate the perception that its introduction in commercial real estate is limited to gateway cities where the impact over rent is below 10% (at current price).

- **Operational Expenditures (OpEx):** Not all systems would require annual maintenance. This financial valuation will assume an average annual expense of $300 dollars per system. This number takes into account preventive maintenance of 20% of the units and an annual malfunction in 5% of the units.

- **Capital Expenditures (CapEx):** Real estate income properties usually provision a 2% reserve annually, however the unproven track record of moving furniture on robotics creates uncertainty. Using a conservative approach, 15% of the initial system value will be spent in refurbishment after five years of use.

- **Terminal Value and Replacement Cost:** As described in the previous section, the lifespan of regular furniture and comparable assets occurs over an extended period of time, usually more than ten years. However the robotic furniture technological component might shorten this period due to technological obsolescence. For the purpose of simplicity, the life span of the system is assumed to be 10 years, at which point the system would be replaced at target price ($10,000 USD, corrected for inflation) and disposed at $0 salvage value.

- **Depreciation:** The installation of robotic furniture in a property should be considered an increase in the value of the property and should depreciate at the same rate as the asset. This analysis, however does not take into account the effects of depreciation. Its financial effect on tax shields and its impact on available revenue vary according to the specific tax situation of the country where the building is

located and the owner's tax status, making it difficult to assume an average parameter.

- **Inflation:** All cash flows are projected at a 2% inflation rate annually. This is relevant since the WACC includes an expectation for inflation.

WACC is a metric that weighs the cost of debt and equity to show a blended cost of capital. For the debt cost component of the WACC, it is assumed that the cost of debt at the project level would be the same as the cost of debt to purchase the robotic furniture systems. Costs will vary depending on the leverage level, credit rating of the developer, and the risk perceived by the lender in the project. However, most of the industry should be able to find financing in the range of 5% to 7% and use a leverage ratio close to 60%.

It can be argued that robotic furniture systems suit a wide spectrum of investors. The risk associated with the adoption of the systems is low, as the system performance can be tested in a limited number of units and then expanded if successful. Under this optic, the equity cost component of the WACC is more complex to calculate. Depending on the type of investor and type of project, the range of cost of capital will vary greatly. Distinct players in this market can illustrate this situation, including:

- **Publicly-traded real estate investment firms:** Investors prefer Class A stabilized properties in core markets. This type of investor has a very low risk profile, and the

expected return on equity could be as low as 6%. These investors also could have lower leverage ratios than the industry average.[5]

Real estate developers of speculative projects: Developers that are looking for high returns on equity are usually willing to develop projects in unconsolidated markets. On this side of the spectrum it is also common to find opportunistic private equity funds, which target returns of up to 25%.

Having defined the equity cost ranges of different investors, it is possible to construct a table for a relevant range of WACC rates to evaluate the NPV produced by robotic furniture.

Figure 20 WACC parameters and sensitivity

WACC Base Assumptions	
Leverage Ratio	60%
Cost of Equity	18%
Cost of Debt	5%
WACC	10.8%

	12%	16%	20%	24%
4%	7.2%	8.8%	10.4%	12.0%
5%	7.8%	9.4%	11.0%	12.6%
6%	8.4%	10.0%	11.6%	13.2%
7%	9.0%	10.6%	12.2%	13.8%

[5] Market public data is only available for Real Estate Investment Trusts (REITs), which accounts for a very specific profile of real estate investors accordingly to The National Association of Real Estate Investment Managers. (NAREIM) betas for REITS in broad range, "during the "modern REIT era" has generally fluctuated between 0.48 and 0.82". Using these betas, and using NAREIM's reported average REIT leverage of 45% we can come up with an approximate for return on Equity for this type of investor using CAPM.
Calculating 5.5% risk premium for real estate development and 2.55% risk free rate, the range for cost of equity for REITS is between 6.82% and 15.31%.

Our WACC base assumption will be on the higher end of the calculated spectrum at 12.6%. Current interest rates are at historic minimums and expected increases in the risk free rate by the FED will increase the cost of debt and equity both, providing good reasons to use this WACC. Another reason to use a higher WACC is to allow the financial analysis to cover most of the investors and developers spectrum, not only those with access to inexpensive capital.

5.2.2. Discounted Cash Flow (DCF) Valuation of Robotic Furniture

Different capital events in the life cycle of robotic furniture can be segmented in the following categories.

- **System Acquisition:** This cash flow is the initial cost of purchase and installation of the system. Because this event happens in time period 0, there is no discount on the value.

Figure 21 System purchase cash flow

	NPV	0	1	2	3	4	5	6	7	8	9	10	11
System Purchase	-$20,000	$20,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0

- **System Net Operating Income:** The operational cash flow from Robotic furniture is the potential rent premium generated by the system minus the expected average

vacancy of the property, the operational costs to maintain the system (OpEx) and the capital expenditures (CapEx).

Figure 22 Operation cash flow

	NPV	0	1	2	3	4	5	6	7	8	9	10	11
Pot. Rent premium	$15,952	$0	$2,693	$2,747	$2,802	$2,858	$2,915	$2,973	$3,033	$3,093	$3,155	$3,218	$0
Vacancy	-$798	$0	-$135	-$137	-$140	-$143	-$146	-$149	-$152	-$155	-$158	-$161	$0
Eff. Rent premium	$15,154	$0	$2,558	$2,609	$2,662	$2,715	$2,769	$2,824	$2,881	$2,939	$2,997	$3,057	$0
OpEx	-$1,813	$0	-$306	-$312	-$318	-$325	-$331	-$338	-$345	-$351	-$359	-$366	$0
CapEx	-$1,830	$0	$0	$0	$0	$0	-$3,312	$0	$0	$0	$0	$0	$0
NOI	$11,512	$0	$2,252	$2,297	$2,343	$2,390	-$874	$2,487	$2,536	$2,587	$2,639	$2,692	$0

- **System Replacement:** The expected value of replacement of the system due to wear and tear or technological displacement in the tenth year.

Figure 23 System replacement

	NPV	0	1	2	3	4	5	6	7	8	9	10	11
System Replacement	-$3,370	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	-$12,434

- **Asset Sale Price Increase:** The adoption of robotic furniture increases the potential rent of the property and raises the Net Present Income (NOI). Since the value of the property is determined by its income, the use of robotic furniture increases the sale price by the cap rate used for sale.

Figure 24 Robotic furniture effect on building valuation

	NPV	0	1	2	3	4	5	6	7	8	9	10	11
Asset Sale price increase	$12,160	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$44,859

Under the current economic environment, property buyers are looking for alternative methods to increase value, since cap rate compression seems to have hit bottom. An increase of $2,208 USD (NOI before inflation) at a 6% cap rate means an increase in value of $36,800 USD per unit that installs the system.

- **Robotic Furniture Before Tax Cash Flow:** The total cash flow generated by the system is the sum of acquisition, NOI, System Replacement, and Asset price increase

Figure 25 Robotic furniture before tax cash flow

	NPV	0	1	2	3	4	5	6	7	8	9	10	11
RF bef. tax CF	$3,831	$20,000	$2,252	$2,297	$2,343	$2,390	$874	$2,487	$2,536	$2,587	$2,639	$2,692	$32,425
IRR	12.8%												

The net present value of all cash flows generated by the implementation of robotic furniture is equal to $301 USD. This means that the return of the system is above the required WACC. In fact, with the assumptions for this cash flow, the return of robotic furniture is 12.8%, meaning that it will enhance the financial performance of the property for investors.

In this valuation it is important to emphasize that micro unit issues of vacancies and high turnover rates could potentially be mitigated by the use of robotic furniture, however the increase in valuation from these causes would be highly speculative and is excluded from the analysis.

5.2.3. Sensitivity Analysis

The financial analysis presented establishes that the inclusion of robotic furniture makes sense from a financial standpoint within the described parameters. However, the parameters used in the evaluation are restrictive to a very specific type of product in limited markets. This section tests those parameters to determine which financial conditions must be achieved by the technology to be NPV positive for different investors in different markets.

The most critical assumption for technology adoption in the financial analysis, which has not been discussed in detail, is the cost of the system. Any projection or assumption in this regard is unlikely to be accurate with the available information. To overcome this problem, the present sensitivity analysis will estimate the price of the system as the residual value of the NPV = 0 calculation of the presented model. For the previous section, at an NPV of $301 USD the residual cost of the system would be $20,301 USD.

First adopters of robotic furniture will face uncertainty on key variables. However, the rent premium will be less of a problem since the high-end market in target cities can easily support the assumed premium. For these property owners, the operational expenditures and the replacement costs will be the major uncertainties. The next table tests the residual price of the system at different levels for the discussed parameters.

Figure 26 Sensitivity analysis 1

Replacement cost	&	Maintenance
Variance		Variance
+/- $2,500		+/- $150 monthly

Replacement cost\OpEx	$150	$225	$300	$375	$450
$7,500	$24,096	$23,230	$22,364	$21,497	$20,631
$8,750	$23,675	$22,809	$21,942	$21,076	$20,210
$10,000	$23,254	$22,387	$21,521	$20,655	$19,789
$11,250	$22,832	$21,966	$21,100	$20,234	$19,367
$12,500	$22,411	$21,545	$20,678	$19,812	$18,946

An increase of $2,500 USD for replacement costs reduces the residual value of the system below the target $20,000 USD only when the operational costs exceed the budgeted $300. Figure 25 shows that uncertainty around replacement costs and maintenance are not critical factors in deciding on the adoption of the system.

Different cities in the same country show major differences in rents, and these differences increase when comparing across nations. If "renters expectations [that] micro-units [will] be 21 to 30 percent less [rent] than a comparable studio"[5] is constant across markets, the calculated rent premium of $220 USD for robotic furniture must be significantly lower in second tier cities across the U.S.

Cost of debt and equity as discussed in section 5.2.1 could have a wide spread depending on the type of property and the investor. The next data table presents the residual value of the system at different levels of rent premiums and investors' WACCs.

Figure 27 Sensitivity analysis 2

Rent Premium	&	WACC
Variance		Variance
+/- 25%		+/- 20%

Rent Premium/WACC	10.1%	11.3%	12.6%	13.9%	15.1%
$165	$15,442	$14,180	$13,060	$12,062	$11,171
$193	$19,768	$18,133	$16,680	$15,388	$14,235
$220	$24,094	$22,085	$20,301	$18,714	$17,299
$248	$28,419	$26,037	$23,922	$22,040	$20,363
$275	$32,745	$29,989	$27,543	$25,367	$23,427

Results exhibited in **figure 26** confirm the assumption that the rent premiums required to allow the adoption of robotic furniture systems at current prices are restricted to top tier markets. However this table also predicts markets in which the technology will be adopted as costs decline. Markets capable of sustaining $165 USD premiums for the system would be NPV positive for institutional investors with lower cost of capital when the system reaches prices below $15,000 USD.

The last sensitivity analysis will alter the assumptions for the final cost. The $10,000 USD target cost assumes an increase in functionality and high end finishes consistent with the type of property in which it was initially installed. However, if robotic furniture becomes popular it is expected that competing systems from rival firms will follow shortly thereafter. This simulation will change the replacement cost to $5000 USD while reducing the operational expenditures by half (assuming cheaper system costs and lower labor costs in emerging markets). Testing the

value of the system around a target premium of $66 USD is consistent with a monthly rent of $700 USD.[6]

Figure 28 Sensitivity analysis 3

Rent Premium	&	WACC
Variance		Variance
+/- 40%		+/- 20%

Rent Premium/WACC	10.1%	11.3%	12.6%	13.9%	15.1%
$40	$930	$881	$838	$798	$763
$53	$2,846	$2,619	$2,420	$2,243	$2,086
$66	$4,762	$4,357	$4,001	$3,688	$3,410
$79	$6,678	$6,095	$5,583	$5,132	$4,733
$92	$8,594	$7,833	$7,165	$6,577	$6,057

This table demonstrates that robotic furniture isn't feasible for most emerging markets unless significant drops in prices are achieved. However, these results, like all others in this document, rely on the assumption that users will value a square foot generated by robotic furniture at least as much as they value 0.5 SF of real constructed space. If public perception of the value generated by robotic furniture were higher, the relationship between the unit rent and the system rent premium could also increase, such that robotic furniture would make financial sense in emerging markets.

[6] Studio rents in middle class neighborhoods in emerging cities like Mexico, Bogota, Mumbai, Shanghai or Sao Paulo range between $600 and $800 USD, according to the author's market research.

6. Conclusion

Even if it seems that our homes are the final frontier for robots, the current environment of low cap rates, high rent prices and a renewed interest in urban living could provide the right combination for robotic furniture systems to finally flourish. The present analysis has focused on currently available technology to evaluate and simulate the business decisions that developers will face as they adopt robotic furniture in coming years.

The present analysis chooses to leave out most of the infinite possibilities[7] that furniture capable of sensing and changing according to its environment might provide for tenants and building owners. Adaptable furniture will create possibilities such as tracking space usage, generating and selling digital content for homes and/or installing apps that track users' habits to enhance their health. All of these features could potentially bring real estate to the world of downstream revenue, in which building owners could collect a portion of the profits from the sales happening inside of their units. Not to mention advantages that this technology could provide from the property management standpoint.

Despite all of the interesting profit possibilities that robotic furniture might bring in the future, business decisions, particularly in the traditional industry of real estate, are based on facts and tangible assumptions. Among all the possibilities offered by robotic furniture, the most important and tangible benefit is the ability to increase usable area in a residential unit. Using one of Morphlab's proposed systems, which transforms into a bedroom, walk-in closet, living area, and

[7] Finance theory defines these as real options, which are commonly left out of financial analysis due to the high complexity and uncertainty that they create in valuations.

study on demand, this thesis calculated the increased usable area to be 71 square feet, an increase of 17% in a 400 square foot studio. Even though a straight comparison of usable and real area is far from objective, this metric provides a starting point to calculate rent premiums and financial analysis of the technology's adoption.

The DCF analysis for adoption of robotic furniture in commercial properties demonstrates its financial viability, but more importantly shows the potential of the technology to increase property value. This is an important issue for the industry as it is clear that value increases through cap rate compression may no longer be available.

As the cost of this technology decreases through the impact of the learning curve and competition, the inclusion of robotic systems will not only impact quality of life in small studios, but could also provide affordable family housing in city centers. This ability to transform space for different demographics makes robotic furniture stand out from other real estate trends.

As best expressed by Ed Glaeser, "building cities is difficult, and density creates costs as well as benefits. But those costs are well worth bearing, because... our culture, our prosperity, and our freedom are ultimately gifts of people living, working, and thinking together." Robotic flexible furniture technology addresses this problem and allows cities to accommodate an increasing population in a confortable and efficient way.

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