

## An integrated approach towards hillside building design for automated construction

Philip Tong<sup>1</sup> and Hans-Christian Wilhelm<sup>2</sup>

<sup>1,2</sup> Victoria University of Wellington, Wellington, New Zealand  
philipjtong@gmail.com<sup>1</sup>, hans-christian.wilhelm@vuw.ac.nz<sup>2</sup>

**Abstract:** In many cities under urbanisation pressures, sloping topographies tend to be under-utilised due to complex designs and difficult access/navigation on-site, resulting in low construction productivity and high cost. Extensive research has been conducted on increasing productivity in the building industry through automation. A similarly prolific area of research from the 1970s and 80s are hillside dwellings that resulted, however, mostly in high-end individual houses. This research combines concepts for automated and prefabricated construction with hillside dwelling design and proposes a method of design that integrates both aspects, generating innovative, site-specific design outcomes. The aim is to develop a parametric framework of design in which site infrastructure for automated construction on hillsides is integrated with the dwelling design to improve productivity and use more affordable hillside sites. Analysis of design typologies for hillside housing and research into automated construction allows for development of high-density, low-rise dwelling structures suited for serial, automation-assisted construction, with the topography as a design-generator. The design method is tested and refined on a case-study site in Wellington, New Zealand. Investigation into the geometric implications of automated construction on hillside sites allows for architects to design so that such processes are incorporated into the building from the start.

**Keywords:** Automated; construction; parametric design; hillside dwelling

### 1. Problem Statement and Relevance

During the process of urbanisation, many cities have sites with sloping or undulating topographies that tend to be either left to informal settlement or to low-density villa-type dwellings. Urbanisation competes with green spaces, which often are limited to hillsides considered too difficult to access for standard construction. The spatial and environmental qualities of urban hillsides therefore often appear compromised and under-utilised, in relation to sustainable urbanism and dwelling design. Undulated topographies also often require complicated design, access, and navigation on-site, resulting in low construction productivity and high cost in turn.

In New Zealand (NZ), where several cities and towns feature complex topographies, low construction productivity has long been identified a major driver of high cost of dwellings (New Zealand Productivity Commission, 2012). One factor of this is a workforce unable to keep up with the growing demand, as indicated by a 2019 Oceania construction market survey (Rider Levett Bucknall, 2019). Introduction of

*Imaginable Futures: Design Thinking, and the Scientific Method. 54<sup>th</sup> International Conference of the Architectural Science Association 2020*, Ali Ghaffarianhoseini, et al (eds), pp. 171–180. © 2020 and published by the Architectural Science Association (ANZAScA).

innovative construction techniques, including prefabrication and the use of automation-assisted practices, can address this labour shortage and increase construction productivity. This in turn would reduce cost of construction on sloped sites and could therefore increase affordable housing supply in cities with undulating topography. However, most existing automation-assisted practices are carried out on flat sites. Given that hillside dwelling typologies tend to be a design typology totally distinct to dwellings on flat sites, application of automation-assisted construction processes to hillside dwellings may require development of a site infrastructure for support. For this purpose, a conceptual shift seems required, away from engineering slopes out (by way of excavation and retaining walls for example), towards a fine-grained analysis of the topography itself, which in turn is combined with parameters driven by dwelling design and construction techniques.

Though often a more affordable land type to purchase, sloped sites offer distinct challenges, and the response to these limitations in NZ tends to be either development of bespoke dwellings, as high-end individual houses, or non-utilisation. Construction of individual houses still represents the largest portion of new dwelling production each year (Stats NZ, 2019), reflecting a largely small scale, traditional construction industry. The requirement for denser urban models and smaller dwelling footprints has been widely acknowledged but lacks implementation. Therefore, exploration of innovative design and construction techniques, including automation, seems best suited to Medium Density Housing (MDH) or low-rise, high density housing typologies, allowing for a higher urban density within cities. This typology would also allow for an increase in affordable housing; compared to traditional low-density typologies, greater density means also greater supply.

With this in mind, the paper focuses on exploration of options for increasing construction productivity, through application of contemporary technologies such as prefabrication and automation; it also focuses on development of a hillside medium density housing typology that fits within the New Zealand context and integrates principles of sustainable urbanism including higher densities and ample green spaces; and finally, exploration of the potential for the adaptation of existing automation-assisted construction practices for hillside sites, in order to allow the less-expensive hillside land type to be more affordable to build on, thereby achieving more sustainable and liveable dwelling models within cities.

## 2. Background Research, Proposition, Methodology

**Literature Review.** The tension or antithetic relationship between construction productivity and adaption to changing sites and requirements is inherent to architecture and construction. With the establishing of industrial production, in the early 1900s, architects and engineers have aimed to transfer concepts from mass production of consumer goods to production of dwellings or buildings. Research by Seelow (2018) on these early concepts shows that, though technology has changed drastically since then, ideas developed by Walter Gropius are still of interest for the conceptualisation of the construction site as an assembly line and the idea of serial construction from a flexible kit of components. The rationality behind Gropius' concepts is that the component itself, being manufactured as a mass-produced item, could have flexibility in terms of configuration within the resulting structure. While the assembly-line principle has been readily adopted, the construction kit approach towards construction has not seen the same level of adoption. The industry is well-suited to the adoption of components and modules, as reinforced by prefabrication design guides by both Knaack *et al.* (2012) and Smith (2012), which look at both theory and practical considerations for designing using prefabricated elements.

Current research into application of in-situ automated construction focuses on strategies and techniques for assembly, and, with few exceptions, are carried out on flat sites or in controlled production environments (for example, the in-situ fabricator and the mesh-mould wall, as explored by ETH Zurich) (Hack, 2018). For on-site automation, advanced navigation assisted by real-time scanning of the surrounding space has been explored for developing mobile robots with varying tools. Further explorations of potential for in-situ processes have been investigated (among others) by Helm *et al.* (2012) and Keating *et al.* (2017). Helm *et al.* discuss the requirements for on-site processes, including the limitations, whereas Keating *et al.* investigates architecture-scale robotic prefabrication and application of the processes. An assessment of the effects of the robotic fabrication process on design has been discussed by Bonwetsch (2012): inclusion of the principles of the fabrication process into the design can result in the design being inherently buildable without requiring analysis and adaptation to a buildable product, and can reduce losses between the conception and the construction of the design.

There is a significant amount of research carried out in terms of construction and design on sloped topography, primarily around the 1980s. Rouillard (1987) and Levin (1991) identify general principles of hillside structural, aesthetic, and programmatic decisions, while Simpson and Purdy (1984) examine the pragmatics of construction on hillsides. A more contemporary analysis of hillside designs by Burns and Kahn (2004) focuses on how site can be used a design driver, to result in architecture that is properly integrated with the environment. These examples are limited to the technologies of the time, and to bespoke projects, as opposed to affordable dwellings. In light of the above, the research gap identified is for an integrated design method, comprising site specific responses, automation-assisted production and assembly, and a design and construction kit allowing for economy of scale.

**Research proposition.** This paper proposes that adaptation of automation-assisted construction practices for hillsides, and the development of a design method in which the required site infrastructure is integrated, can increase construction productivity on sites with sloped topography. The focus of the paper is on adaptation of existing techniques and processes for hillside construction, for the purpose of developing low-rise, medium-density housing.

**Methodology.** The research comprises three main methodological steps: firstly, establishing typologies for the relationship between site and dwelling, and general research into hillside dwelling design. Secondly, analysis of typologies of current techniques for construction automation. In a final step, the findings from the initial steps are used to formulate a parametric framework for design and siting of medium-density, low-rise dwelling structures suited for serial, automation-assisted construction. The topography will be used as the main parameter in this process. The resulting design method is tested and refined on a case-study site in Wellington (NZ).

### 3. Research Steps and Findings

#### 3.1 Typological analysis of hillside dwellings and construction automation/robotics

**Typologies of hillside dwellings.** The initial steps focus on case studies: identification of hillside dwelling typologies that have a strong relationship to the sloped topography is important, as the desire is to develop a dwelling that is specific to hillsides. Establishment of general hillside typologies allows for a basic knowledge of some design strategies for how the geometric form of the building could relate to the slope. With the learning from the general typologies, a matrix of precedent hillside dwellings has

been established from both international and NZ projects. The elevated typology, or more colloquially the stilt house (Figure 1a), is a prominent response within NZ to the hillside condition. In combination with the fact that stilts have less of an impact on the site itself and require less earthworks, this typology has been chosen for further exploration into adaptation for an automation-assisted construction typology.

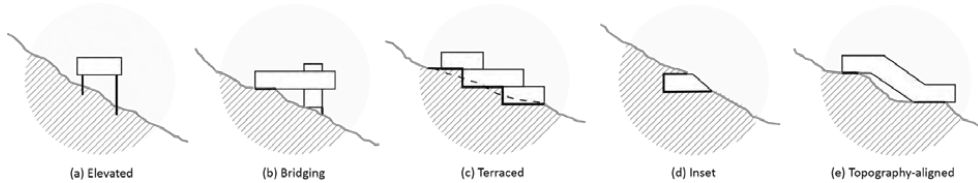


Figure 1: Examples of hillside typologies

**Typologies of current techniques for construction automation.** A similar analysis of the general techniques for construction automation has been carried out, exploring the geometric implications of using automation-assisted construction processes. The characteristics that serve as the primary focus for this matrix are firstly the mobility of the automation, or the ability for the automation to relocate itself; secondly the reach of the automation, or the range in which the automation could work in before requiring relocation. These general automation typologies range from the factory setting automation, wherein the automation is permanently fixed inside a structure, but has a greater range and payload (Figure 2a); to the mounted unit automation, where the automation is attached to a mobile platform of some kind, but tends to have lower range and payload (Figure 2e).

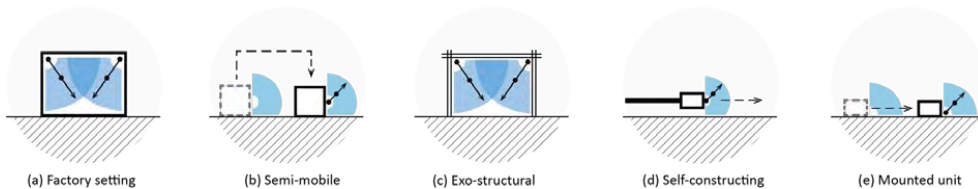


Figure 2: Examples of automation typologies

**Conceptual assembly strategies.** The two discussed categories of analysis then have been overlaid with each other to develop three initial concepts, that incorporated theoretical automated construction processes:

- The sequential fabrication process, in which an initial structural assembly is constructed, and then used to support a robotic crane. Further assemblies are then constructed to support modules moved into place. Using the built assemblies as support, the robotic crane (or a pair) can be progressively moved, allowing for construction to continue uphill (Figure 3a).
- The spine and unit process, in which a spine assembly is constructed first by a mobile automation, which then uses the spine to advance and continue building. The units are then constructed out

from the spine (Figure 3b). During and after construction, access and service infrastructure is located in the spine.

- c. The funicular assembly process, in which a funicular railway system is used as a central point from which the automation works, as it constructs the dwelling around it. This limits the dwelling to a relatively linear shape, due to how the funicular functions (Figure 3c).

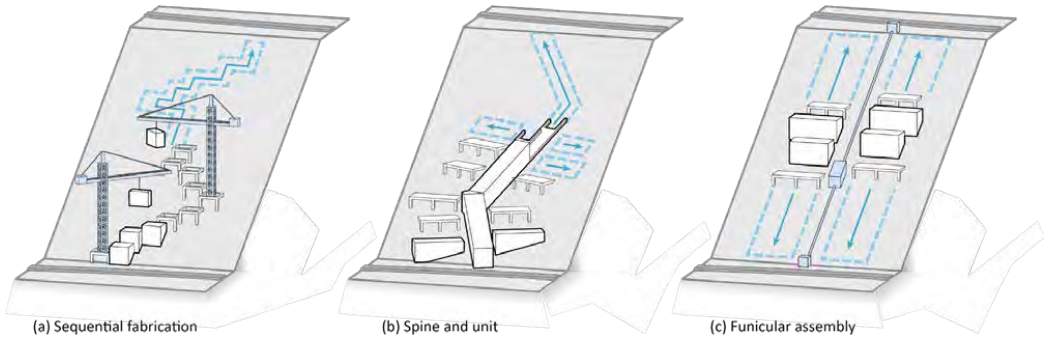


Figure 3: Conceptual assembly strategies

### 3.2 Developing an integrated, analytical design method

**Case study.** In order to test and develop the initial concepts, a complex and steep hillside at Shelley Bay on the Miramar Peninsula in Wellington (NZ) has been identified. This area is likely to be developed for densified urban development, and exemplifies the problems associated to hillsides as described in section 1. Furthermore, Shelly Bay has garnered criticism for issues such as a lack of affordable housing and public spaces, inadequate scale of buildings perceived as too large, and infringing excessively on the forested green spaces. The specific site selection identifies an area between Shelly Bay Road and Main Road, just south of Carter Park, on the edge of a forested area. Based on the initial design concepts, aspects of the sequential fabrication and spine and unit processes are selected for further development on the specific site. The sequential fabrication strategy has the greatest potential for adaptation to for a modular prefabricated system. The spine and unit concept has a better programmatic layout, however, with a shared pathway for access and infrastructure from which all dwellings can be accessed.

**Formulation of parameters for a design method.** For the envisaged method of design, the strategy comprises two steps and a combination of parametric and manual design processes: firstly, developing a script able to determine possible sites on an input topography, and generate a structure. Secondly, manual manipulation of the output, dependant on qualitative criteria, into a dwelling. The script here is understood as an analytical design method or tool, which can be applied to other instances of the same environment, with an output that allows for automation-assisted construction. Vice-versa, the output from the script is not understood as an entire design in and of itself.

The first structural decision to be made is around the foundations of the site. Screw piles present an opportunity for automation-assisted processes: there are existing practices that incorporate machinery

in the screw pile installation process, simply requiring a rotary hydraulic powerhead to wind the pile into the ground. The potential for adaptation of an automation such as the In-Situ Fabricator (a caterpillar-tracked mounted unit) for installation of screw piles is evident, due to the similarity of some existing machines for screw pile installation. Indicative values for maximum slope are taken from the Caterpillar Performance Handbook (Caterpillar Inc., n.d.), where any slope above 25° is to be treated as Extreme. Prefabricated volumes or pods, comprising 1-2 rooms, are laid out on a grid generated where the robot can access, and are supported on bearers and the screw-in foundations. The volumes are positioned to have interstitial spaces that can either form part of the dwelling, or used as accessway (Figure 4a-c).

**Defining a three-dimensional grid for spatial slope analysis.** The scale of the repetitive grid, and of the floorplates, is driven by both the story height and the requirements for stairs. The storey height of each volume was decided to be 3.2m, to allow for comfortable floor-to-ceiling height. The resulting 1.6m half-storey height informed the stair dimensions: given that the accessway should conform to Accessible stair standards as set by NZBC Clause D1, the maximum pitch of the stairs should be 32°. To rise 1.6m, the stairs would require a minimum length in plan of approximately 4.5m including landings at the top and bottom. To accommodate the stairs, the volumes are intended to have side lengths of 5.1m. In combination with the width of the stairway itself, the overall grid spacing was input as 7.2m (Figure 4d).

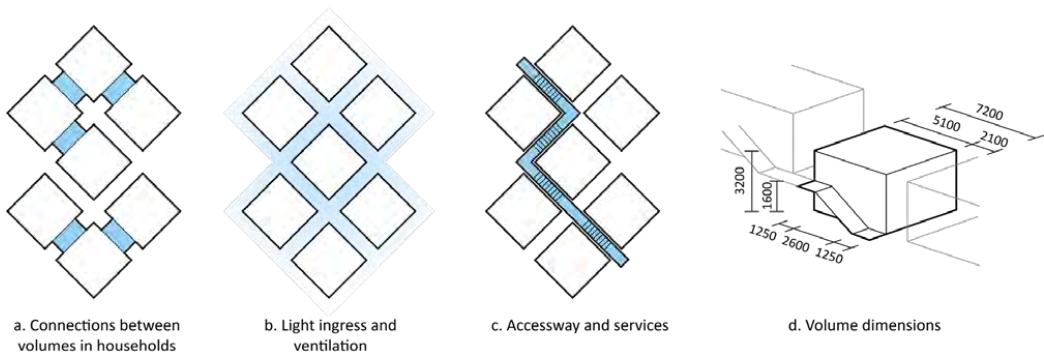


Figure 4: Interstitial space purposes and volume dimensions

The grid itself was angled at 45° from the face of the slope, as it resulted in the volumes staying better connected adjacently, compared to un-angled. Other site-specific advantages of angling the grid include two of the faces of each volume now having better potential for good views across the harbour, compared to one, and the potential for better access to sunlight (especially when regarding the hill).

Visual scripting (Rhino Grasshopper) has been used for slope analysis and generating the geometry for developing the design. There are benefits to using generative design tools for certain purposes: generative design tools manage to take input parameters, and using a specific set of rules, develop a response. In this way, generative design can be viewed as a quantitative response, as opposed to the qualitative characteristics that manual design is more suitable for. In finding the rules for an automation-assisted construction process, it is possible for a script to be developed.

### 3.3 Defining the generative script

**Slope angle analysis and location of a valid point grid on the topography mesh.** Initial scripted generation requires identification of the areas of the topography that can be accessed by the robotic unit, and application of the point grid (of dimensions decided beforehand) to the valid areas.

- a. Generate a NURBS surface, representative of the sloped site, from contour polylines
- b. Explode the NURBS surface into constituent triangular faces, and analyse to find slope of the face
- c. Group the faces by slope, depending on a maximum angle input parameter (in this case,  $25^\circ$  is the maximum slope, so faces are grouped by whether they are faces of desired slope or not)
- d. Input analysed faces into a green-to-red colour gradient, and blur, for visual representation
- e. Generate a field of points on the XY-plane that corresponds to a square grid. The size of the square grid is an input parameter and decides the distances between interstitial intersection points. This grid is rotated  $45^\circ$
- f. Project the faces that have the desired slope down flat onto the XY-plane, and find the points of the grid that fit inside the projected faces
- g. Project these select points up onto the topography mesh, so that they land on the surface, but only on the faces with desired slope. This method ensures that only the faces of the desired domains will have points applied to them.

**Locate floorplates in valid positions and generate stilts and volumes.** Once the point grid has been applied to the valid areas, floorplates are generated where piles can support all four corners and moved to the input storey spacing. Floorplates can be used to generate stilts and can be extruded to volumes.

- a. All floorplates are moved up to the nearest altitude of a specific factor: the input parameter that defines the levels of the floorplates (the vertical spacing between floorplates)
- b. Find all floorplates that intersect the topography mesh and translate vertically, for properly valid floorplate location
- c. From the corners of the floorplates, project lines straight down to the topography mesh, representing stilts, and allowing for identification of pile locations (Figure 5)
- d. Extrude the floorplates into volumes.

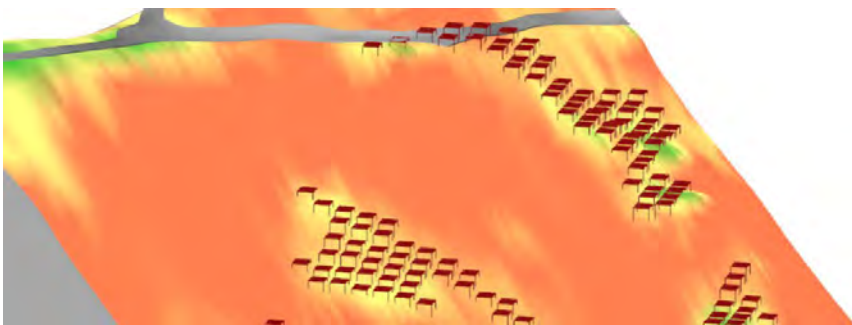


Figure 5: Floorplates located in valid positions

**Accessway Pathfinding.** A base pathway for the shared accessway can be generated from a set of criteria including maximum vertical coverage, use of paths that have correct stair pitch, number of household units that can be accessed, and maximum straight sections.

- a. Floorplates are grouped into the overall clusters of floorplates, and three points are generated from these, all in the interstitial intersections: a randomized selection of one point each from the lowest 20%, middle 20% and highest 20% of all interstitial intersections (in terms of z-value)
- b. The three points are used to generate a polyline representing the general trend for the accessway to follow. The actual accessway path is generated from lines representing all possible locations for a pathway to follow that conforms to stair requirements, and follows the general trend polyline as closely as possible
- c. An algorithm solver manipulates the three generated points many times in quick succession, generating many possible pathways that are then analysed to best fit a set of criteria:
  - ☐ Pathways that maximise vertical distance covered between top and bottom points
  - ☐ Pathways that do not double back on themselves
  - ☐ Pathways that have relatively even numbers of volumes on either side
  - ☐ Pathways that have as few corners to turn as possible

The algorithm provides a number of different paths that can then be manually reviewed: however, all paths identified with this method require further development. Due to the limitations of the pathfinding tool, unnecessary corners are often added. It is desirable to maximise the straight sections of the accessway path for visual confirmation of where the pedestrian is going, as well as to increase safety by minimizing corners that conceal the path ahead (Figure 6a).

**Household unit identification and volume refinement.** Manual decision-making allows for the volumes to then be further refined into dwellings, starting with volumes around the accessway: the removal of certain volumes at some of the corners of the shared accessway can introduce views to those selected corners, providing destinations along the accessway.

Manual identification of the household units is possible once the accessway path has been recognised. A connection to the accessway is always required, and the household units therefore branch off from the central path. The household units consist of clusters of 3-5 volumes, with or without a void volume to form a courtyard (Figure 6b). Clustering of households needs to take into account factors such as vertical displacement between adjacent volumes, to allow internal stairways to be possible. The household units consist of varying numbers of volumes due to the variance in requirements for households in NZ, allowing for a range of household occupant numbers. The varying number of volumes also allows for more adaptability when laying-out the household units themselves (Figure 6c).

Manual identification of the household units is desirable, as there are many potential qualitative factors alongside the quantitative factors (e.g. the requirement for volumes to be on similar levels for access). These qualitative factors could include aspects such as the views possible from certain locations, or which volumes would be most appropriate for removal and use as a garden/courtyard, and how those voided volumes can then be used as part of select households. Given the limitations of parametric generation as a quantitative tool, qualitative decision-making is not a possibility for the script, hence the manual input.



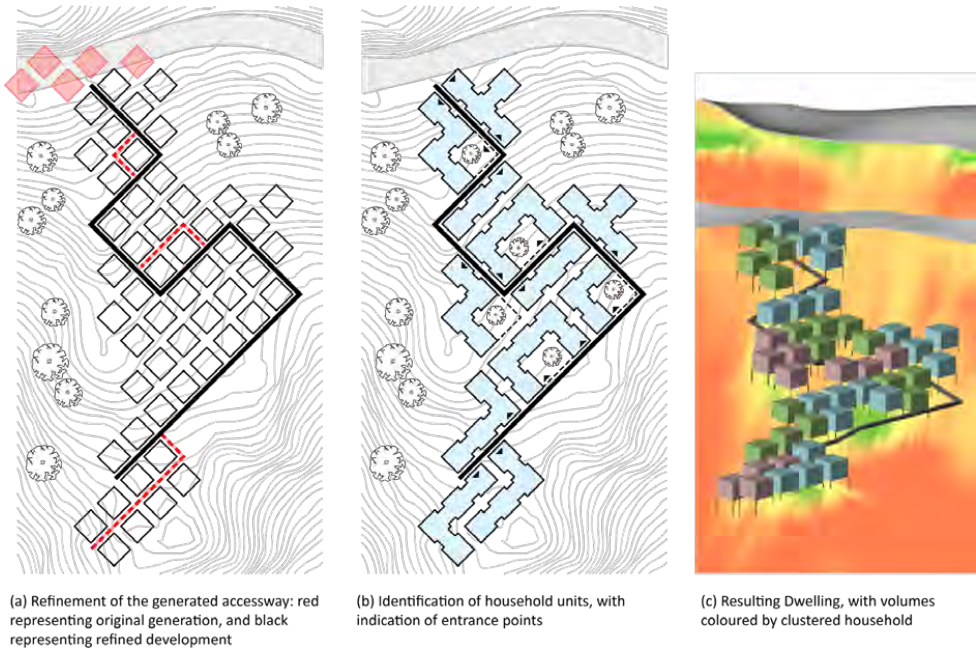


Figure 6: Further refinement of the generated dwelling

**Further considerations.** Volume scale will need to consider the specific structure and design of the prefabricated components. As the current method of construction is for combination of robotic caterpillars and robotic cranes to place modules on-site, the ability for a module to be transported is major factor for scale: the maximum width of a module without requiring oversized load approval is 2.50-2.55m, 4.25-4.30m tall, and 20m long (NZ Transport Agency, 2017). The material for the structure itself will also affect the dimensions of the volumes.

Planning out the household floorplans themselves have many further considerations. There is potential for the volumes to be two- or three-level volumes instead, increasing the size of the floor area per household, though this would increase shading in the interstitial spaces. The implication of investigating this could affect the method for identifying household units themselves: if the volumes contain multiple levels, less volumes are required per household. Another aspect that needs to be considered is the requirement for privacy, avoiding overlooking windows in adjacent households.

The proposed system identifies methods for applying automated construction to hillsides for the purpose of increasing construction productivity, as the inherent advantages of automation-assisted construction can allow for an increase in the efficiency of the work carried out on-site. Through the use a parametric framework, the topography of the site itself can be used as an input for generation of a structure that allows for the identified processes to be carried out, and can support manual development into a multi-unit dwelling.

## Implications

The design tool developed in this paper allows for synthesis of the efficiency of hillside automation-assisted construction, through the input parameters. The modular approach allows for efficient space use and easier application of prefabricated design principles. The proposed system appears to have high potential within the NZ context: maximising the amount of work carried out by automated means decreases the need for a large number of manual workers, thereby lessening the impact of a decreasing available workforce. In combination with prefabrication, less time on-site is also required. By integrating the requirements for automation-assisted construction into the design process, buildability is incorporated into the building from inception, lessening the potential for transfer loss between design and construction when analysing the design for buildability at later stages. These characteristics are indicative of an integrated design method with the potential to positively impact hillside construction and allow for better design and more efficient use of hillside sites.

## References:

- Bonwetsch, T. (2012) *Robotic Assembly Processes as a Driver in Architectural Design*. Available from: ETH Zurich <<https://www.research-collection.ethz.ch/handle/20.500.11850/59658>> (accessed 19 June 2020).
- Burns, C. and Kahn, A. (2004) *Site Matters: Design Concepts, Histories and Strategies*, Routledge, New York.
- Caterpillar Inc. (n.d.) *Caterpillar Performance Handbook*. Available from: Caterpillar Inc <[http://nees.ucsd.edu/facilities/docs/Performance\\_Handbook\\_416C.pdf](http://nees.ucsd.edu/facilities/docs/Performance_Handbook_416C.pdf)> (accessed 21 July 2020).
- Hack, N.P. (2018) *Mesh Mould: A Robotically Fabricated Structural Stay-in-Place Formwork System*. PhD Thesis, ETH Zurich, Zurich.
- Helm, V., Ercan, S., Gramazio, F. and Kohler, M. (2012) Mobile Robotic Fabrication on Construction Sites: dimRob, *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 7-12 October. Vilamoura: IEEE.
- Keating, S.J., Leland, J.C., Cai, L. and Oxman, N. (2017) Toward site-specific and self-sufficient robotic fabrication on architectural scale, *Science Robotics*, 2(5), 1-15.
- Knaack, U., Chung-Klatte, S. and Hasselbach, R. (2012) *Prefabricated Systems: Principles of Construction*, Walter de Gruyter GmbH, Berlin.
- Levin, A.H. (1991) *Hillside Building: Design and Construction*, Arts + Architecture Press, Santa Monica.
- New Zealand Productivity Commission (2012) Housing Affordability Inquiry. Available from: New Zealand Productivity Commission <<https://www.productivity.govt.nz/assets/Documents/9c8ef07dc3/Final-report- v5.pdf>> (accessed 29 July 2020).
- NZ Transport Agency (2017) *Vehicle dimensions and mass: guide to the factsheet 13 series*. Available from: New Zealand Transport Agency <<https://www.nzta.govt.nz/resources/factsheets/13>> (accessed 23 July 2020).
- Rouillard, D. (1987) *Building the Slope: Hillside Houses 1920-1960*, Arts + Architecture Press, Santa Monica.
- Rider Levett Bucknall (2019) *Oceania Report: Construction Market Intelligence*. Available from: Rider Levett Bucknall <[https://s28259.pcdn.co/wp-content/uploads/2019/01/RLB-Oceania-Report\\_Q1\\_2019\\_2.pdf](https://s28259.pcdn.co/wp-content/uploads/2019/01/RLB-Oceania-Report_Q1_2019_2.pdf)> (accessed 18 July 2020).
- Seelow, A.M. (2018) The Construction Kit and the Assembly Line – Walter Gropius’ Concepts for Rationalizing Architecture, *Arts*, 7(4), 95-124.
- Simpson, B.J. and Purdy, M.T. (1984) *Housing on sloping sites: a design guide*, Construction Press, London.
- Smith, R.E. (2010) *Prefab Architecture: A Guide to Modular Design and Construction*, Wiley, Hoboken.
- Stats NZ (2019) Building Consents Issued: December 2019. Available from: Stats NZ <<https://www.stats.govt.nz/information-releases/building-consents-issued-december-2019>> (accessed 28 July 2020).