sustainability

MDPI

Article

Architectural and Configurational Study of Senior Housing with Steel Volumetric Modular Technology: Towards Age-Ready and Process-Efficient Sustainable Living

Bartłomiej Hominski [1], Filip Suchoń [1,*], Karol Wawrzkiewicz [2] and Ewelina Woźniak-Szpakiewicz [1]

[1] Faculty of Architecture, Cracow University of Technology, 31-155 Kraków, Poland; bartlomiej.hominski@pk.edu.pl (B.H.)
[2] Discipline Architecture and Urban Sciences, Doctoral School of Cracow University of Technology, 31-155 Kraków, Poland
* Correspondence: filip.suchon@pk.edu.pl

Abstract: The aging population requires housing developments that can adapt to their changing needs. The study examines the use of steel volumetric modular technology to construct collective senior housing for independent, sustainable living. The authors explore the qualities of senior housing projects through a literature survey and case studies. Projects appreciated in the architectural industry, illustrating the best practices, are considered. For the development part, the feasible design variants are proposed, BIM modeled, and expertly assessed. Optimization of the types and numbers of modules is carried out to make the most effective use. The potential for generating appropriate flow and social interaction in the shared spaces is also tested. The results prove that a single dwelling unit may embody many features of a suitable architecture for older adults and be used to construct collective senior housing buildings. However, a 3D module with two rooms on either end and a corridor in the middle (the most economical form of 3D prefabrication) is unsuitable for senior housing. Additionally, a narrow 3D module cannot accommodate a complete dwelling unit due to increased dimension needs. Designers and builders must balance economics with the requirements of aging residents to widen the range of volumetric prefabrication areas.

Keywords: volumetric prefabrication; aging in place; sustainable housing; collective senior housing; prefabricated pre-finished volumetric construction; circular economy; isovists

Citation: Hominski, B.; Suchoń, F.; Wawrzkiewicz, K.; Woźniak-Szpakiewicz, E. Architectural and Configurational Study of Senior Housing with Steel Volumetric Modular Technology: Towards Age-Ready and Process-Efficient Sustainable Living. *Sustainability* **2024**, *16*, 3237. https://doi.org/10.3390/su16083237

Academic Editors: Antonio Caggiano and Paulo Santos

Received: 31 January 2024
Revised: 5 April 2024
Accepted: 7 April 2024
Published: 12 April 2024

1. Introduction

Populations around the world are aging rapidly. In 2022, people aged 65 and over accounted for 10% of the world's population, with the largest share in Europe (19%) and North America (17%). By 2050, this figure will increase to 22% [1]. Poland is expected to experience a significant population decline, falling by 18% by 2060. The proportion of those aged 65 and over in the country's population will rise from 18–22% in 2022 to 30–36% in 2060 [2].

As the population ages, the challenges are quantitative and qualitative. Not only do individuals in the autumn of their lives face problems they have not experienced earlier, but their quality of life also often decreases [3], and population aging significantly strains societies' welfare systems. Despite the growing incompatibility between seniors' needs and their homes, many seniors prefer to remain in their current homes due to well-known physical space and community support [4]. However, when housing developments fail to meet the needs of seniors, it limits their activities outside the home, leading to social isolation and reducing their quality of life [5]. To address these issues, "age-ready" cities should be built, focusing on universal design, housing solutions, multigenerational spaces, physical mobility, accessible technology, and efficient spatial forms [6]. The shift towards age-ready environments is reflected in the expansion of solutions related to senior housing.

Recent years have seen an increase in functional and organizational solutions, such as integrated living concepts like co-housing and co-living, that extend seniors' time to lead independent lives and ease the burden of institutional solutions aimed at the elderly [7]. Assisted living concepts consist of a real estate component and a services component, addressing seniors' physical and psychological needs [8].

Innovation in various industries often relies on proven technology from other fields with more significant resources [9]. The hotel industry has inspired some of the solutions aimed at senior housing. In 2015, Marriott, a global leader in hospitality, launched a pilot modular housing initiative in North America. Two years later, Marriott expanded its modular construction initiative, signing contracts for 50 hotels with prefabricated bathrooms or guest rooms. This initiative by Marriott has encouraged investors in the senior housing industry, planning to build senior housing communities exclusively using the offsite manufacturing method with Katerra CLT technology [10].

Chicago-based construction company Skender has worked with large senior housing operators, such as Sunrise Senior Living and Senior Lifestyle Corp. The company hoped that modular technology in senior housing would become the norm, given its benefits of streamlining and reducing investment time. Three companies were to operate under the standard banner of Skender Manufacturing: design, manufacturing, and general contracting. The complexity of operations would result in higher-quality projects, which would be built efficiently and faster, reducing the construction time from 12 to 8 months. As of November 2018, Skender Manufacturing was comprehensively constructing seniors' homes, multi-family homes, healthcare facilities, and other commercial buildings in Chicago [11]. However, the COVID-19 pandemic hampered the company's growth, and it announced the closure of its operations.

On European soil, Swedish furniture giant IKEA and global construction company Skanska are drawing attention with their cooperation resulting in BoKlok, a development company that builds affordable apartments for sale in Sweden, Norway, Finland, and the UK. They use 2D prefabrication technology with timber. In June 2017, BoKlok announced the launch of SilviaBo, a new prefabricated house developed in cooperation with Queen Silvia of Sweden and her charity foundation. The project provides affordable and accessible modular housing for older adults, people with disabilities, and those with dementia. The goal is to offer homes that are created from the beginning with the needs of older adults in mind, rather than ones that need to be altered to meet the needs of seniors as they age. The design considers not only the economic efficiency of construction but also low operating costs, residents' comfort, and sustainability challenges [12,13].

The objective of this study was to create design alternatives that meet the requirements specified in the 2021 call for energy- and process-efficient construction by Polish National Centre for Research and Development (NCBR). The call invited proposals for three types of housing: single-family housing, multifamily social housing, and senior housing [14]. The proposals were required to use modularized, 2D, or 3D prefabrication technology, and the on-site assembly was to be completed within three months. For the senior housing project, the brief called for a building of up to four floors with a lifespan expectancy of 30 years. The functional program comprised 28 apartments of two types for independent living and 200 square meters of shared rooms for residents' use. The NCBR also put forth extensive requirements concerning the proposed technology's energy efficiency and environmental impact. The NCBR anticipates that the development of 2D or 3D technology within the undertaking will help achieve sustainability goals such as providing smaller, yet fully functional apartments tailored to the needs of older people that positively contribute to the well-being of individuals and communities, lowering the maintenance costs for tenants, and developing and providing time- and resource-savvy housing construction.

The contracting authority also noted the requirement for the circular economy by being able to dismantle the building and transport it to another location or to recycle it. NCBR-supported senior housing was expected to respond to the climate challenges and goals outlined in the European Green Deal strategy. NCBR indicated that the building materials used, with a low carbon footprint, were to be primarily recyclable, adding to minimizing the volume of construction waste. The fundamental change was that the buildings would produce energy for their use. At the same time, they are to have very high insulation parameters, which will significantly reduce energy demand to benefit the environment [15].

The following is a summary of a study that was commissioned and funded by DMD-modular, a construction company based in Poland that specializes in 3D modular solutions.

The expected outcome of the commission was to select the best design solutions of a collective senior housing, from an expert's perspective. The purpose of the study was to evaluate the effectiveness of using steel volumetric modular technology for the construction of multiunit senior housing buildings for independent living. The goal was to ensure that the buildings adhered to the best practices in the field without compromising quality. The study identified key architectural elements that make senior housing buildings suitable for older people when compared to other types of dwellings.

2. Literature Review

Modular construction has been progressing and being applied in various ways. Compendia provide insight into modular construction in general. They usually distinguish between 2D (panelized) and 3D (volumetric) prefabrication and focus on the time, workforce, and cost-related aspects of the technologies [16,17]. In 2D prefabrication, the assembly is done onsite, and in 3D technology, the building blocks are fully fitted out off-site. In 3D technology, units made of timber, steel, or, less often, concrete constitute a room or a part of it. The assembly involves hoisting the modules into place and connecting services such as electrical and plumbing, but most of the work is done in an off-site manufacturing facility. However, 3D technology has limitations due to transportation size restrictions (typically around 3.5 m of gross module width), delivery distances, and associated costs [17]. In the European market, volumetric steel modular technology is mostly used in hospitality (hotels, hostels), and affordable and student housing construction [17]. Steel volume prefabrication is thriving due to standard-sized repetitive modules, like hotel rooms or living spaces with bathrooms and kitchenettes. Senior housing is a potential area for expansion, but the evidence is limited so far.

The pioneer of adapting the built environment to the needs of people with disabilities was Selwyn Goldsmith [18]. Later, in the 1970s, Ronald L. Mace, a lecturer and professor of architecture at the University of North Carolina, developed the idea of universal design [19]. This design approach considers the needs of all users and aims to create objects and spaces that everyone can use without the need for adaptation or specific design. The principles of universal design embody seven fundamental values: identical use, flexibility of use, simplicity and intuitiveness of use, noticeable information, tolerance of errors, low level of physical effort, and consideration of dimensions and space for access and use [20]. Nowadays, universal design principles are widely taught in architecture and industrial design.

Regarding collective senior housing, there are a few main currents in contemporary research on the increasingly topical and response-demanding challenges of building homes for an aging society [21].

One stream concerns formal and functional solutions that characterize housing for the elderly and age-ready housing [5,22,23]. These manuals provide insight into the many aspects of designing, building, and running homes for the autumn of life and examples of outstanding projects.

Another stream covers funding and operational management issues. Researchers explore policies for accountability and public-private financing [24] and measures initiated by state agencies to make housing more accessible to older adults [25,26].

The third area of studies focuses on advanced design, construction, and maintenance technologies for modular and intelligent buildings for older people. Researchers used mathematical methods, including BIM, to analyze design options. They built virtual models to analyze walkability, accessibility, and traffic flow in interiors and specific spatial configurations using Space Syntax methodology [27–30]. Spatial configuration is a technical term used to describe how different spaces in a building are connected to one another as a network. This network of spaces plays a crucial role in determining the safety, security, and efficiency of a complex building. By facilitating specific patterns of movement and impeding others, spatial configuration influences not only the movement of people within a building but also its social, economic, and environmental functioning [31]. The paper by Wu and Sober discusses how modular housing can meet the needs of older adults [32]. The design proposals consider a residential area for the elderly in Northern England with flexible plans to meet the varying needs of occupants. The study by Choi et al. looked at guidelines for elderly housing in modular-based prototypes. The prototype followed the analysis of the behavior of the elderly and design guidelines and included a standardized kitchen, prefabricated bathroom, and entrance [33]. The design of residential environments has an impact on people's behavior within it; in the work by Janahi [34], the expected level of newly developed facilities and household privacy are influenced by the neighborhood's social cohesion and dwelling layouts. The connection between shared spaces and casual interactions is also considered.

Despite the existing studies concerning both the living environments of the elderly and the application of prefabrication technologies, there is a noticeable shortage of research that combines the two realms. There is a need for more integrated studies on modular-based senior housing prototypes.

3. Materials and Methods

All structures, which are built to eliminate as much manual labor as possible or replace it with mental planning and machine work, must inevitably be system structures. While in the pioneering phase of prefabrication, the solution to the problem was sought mainly in typification, i.e., in the repetition of layouts and site plan projects, now it was the repeated and typified elements. Therefore, modular systems are not the same as pure prefabrication alone [35]. Instead, there are two fundamentally different approaches:

- Typification: the program and plans are known, and prefabrication follows. When a part is produced, it is known where it will be used;
- Modular system: prefabrication is done before building plans, and the program is available based on assumptions.

Most of the current systems are a hybrid of these two principles [35].

Authors used a 'from the inside out' or 'bottom-up' design method. It involves creating and modeling individual parts and then inserting them into an assembly where they are positioned using mates [36].

It is important to note that the technology used in the study was not the main subject of the research. The commissioning company that manufactures 3D modules uses primarily steel technology. Opting for a steel frame leads to less deforestation compared to timber. As steel frames are produced with precision, they generate less waste. However, the manufacturing process of steel is highly energy-intensive and leaves a significant carbon footprint. Nonetheless, steel is 100% recyclable, which means that after the intense creation process, the steel can be reused and repurposed; it does not require treatment against pests or hazards, which reduces the need for toxic chemicals.

A complex set of methodologies, suitable for different stages of the R&D activities, was introduced (Figure 1). Initially, the strategy was to 'inform the design': gather knowledge and background information and pose research questions. The informing part aimed also to identify the qualities of collective senior housing projects that were important from the point of view of volumetric prefabrication. The authors used a wide range of research techniques. These include:

- Bibliographic research of academic and professional writing on living for the older adults;
- Bibliographic research of professional and technical writing on volumetric modular technology;

- Analysis of manufacturer (research funder) technical documentation;
- Field study in the off-site manufacturer production facility;
- A review of traditional and online resources on built senior housing projects;
- A review of the architectural designs (plans, sections, project statements, and critiques);
- Consulting with the manufacturer as a technology expert.

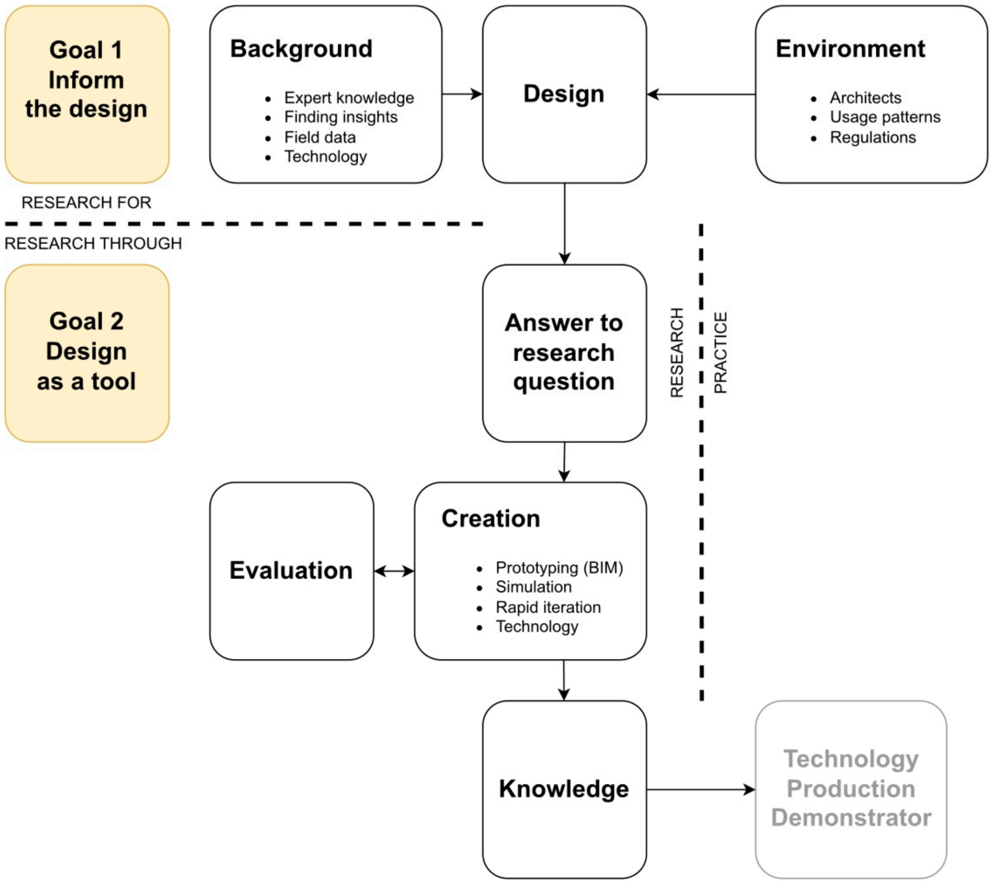


Figure 1. Block diagram of R&D activities. By authors.

After obtaining a pool of background information, the authors undertook the second strategy of 'research by design'. In this strategy, design was considered as a research tool. To this end, the authors first proposed two types of two-module dwelling units (for one- or two-person households). These dwelling units (or 'building blocks') were then used to form three alternative proposals for collective senior housing buildings. The dwelling units and the buildings were developed with emphasis on the qualities identified in the study's first phase.

The simulation method employed was to build a virtual, dynamic model that could be manipulated in time [37,38]. The comparison of simulated results to reality was academically and pragmatically oriented, using elements of theoretical research combined with empirical research and knowledge gained through experiments and simulations.

The design team employed a simulation research approach in the project by creating a digital model in a BIM environment [39,40]. They aimed to explore multiple options for the layout of the modules from the beginning, and successive iterations allowed for the evaluation of each variant. Proposed solutions were tested against various quantitative and qualitative criteria, compliance with regulations and standards, and the 3D module prefabrication technology framework. To evaluate a design variant, authors considered its formal (morphological) and technical qualities, such as appearance, compliance with regulations, functional utility program, ergonomics, and energy efficiency (sustainability):

- Feasible functional quality refers to the suitability of rooms and equipment, efficient use of the building's surface area, operational flexibility, and ergonomics;
- Lower construction and operating costs, maintenance costs, costs of interior refit, equipment and furnishing replacement, and facade replacement characterize feasible economic quality;
- Feasible behavioral quality includes safety (life, health, and property), privacy, territoriality, aesthetics, and physical comfort of the environment;
- Feasible setup quality refers to the interior arrangement adapted to users' needs and accessibility;
- Feasible technical quality refers to the quality and standard of building materials and fixtures.

Space Syntax theory was involved in simulating and predicting user behavior in the specific layouts. Linking users' behavior in space and their social activity to visibility research is based on space syntax and isovist theories, and there is rich and extensive literature on the subject [41–46]. The research methodology was applied with the support of computational techniques. To perform high-speed and high-resolution scans of individual floor plans, we used software from the Isovists platform [47]. Clear visualizations of the distribution of measures such as Co-visibility, Choice, and Integration were obtained. A simulation in the Isovists_App program helped to analyze the legibility of room configurations and ease of orientation in the building's shared spaces. Through the simulation, it was possible to determine the theoretical level of balance between what is seen at a given location and what can be seen through movement from that location. Co-visibility (rV) indicates the degree to which a person at a given site is involved in the reciprocity of "seeing and being seen".

This study has certain limitations. It aims to establish a pool of the constitutive features of architecture for the older adults, but not to prioritize them. Each senior housing project has its own operational model. Consequently, the importance of these constitutive features in projects will vary. The study cannot fully reflect it. Another limitation to the study stems from the lack of established technological standards among the builders that specialize in volumetric construction. Thus, for the purpose of the study, the technical manual from one leading manufacturer was adopted as a technological guideline. Moreover, the study could not consider the importance of the transportation of 3D modules to the construction site, which is another important factor that affects the feasibility of volumetric prefabrication. Finally, despite the fundamental role of the surroundings of any home for the older adults, the study (as stipulated the NCBR call) is conducted for an undefined/abstract site.

4. Results

4.1. Eleven Constitutive Features of Suitable Architecture for the Elderly

The research part aimed to identify the qualities of collective senior housing projects that were important from the point of view of volumetric prefabrication. The authors conducted a review of senior housing developments and analyzed publications related to housing development projects aimed at seniors. The focus of the analysis was on specialized, for-sale, and rental housing for people aged 55 and above who are capable of independent living, and follows the UK's HAPPI (Housing our Ageing Population: Panel for Innovation) guidelines [48]. It should be noted that the study did not cover nursing homes for people with dementia, hospices, or other housing formats primarily designed for people requiring constant and specialized care. The authors analyzed publications in professional papers, books, magazines, industry websites, and websites dedicated to construction for seniors and construction, emphasizing prefabrication. The publications and projects after the year 2000, which the architectural industry appreciated and could represent positive models, illustrate the best solutions in practice.

In the list, the following buildings were among the leading senior housing projects: Heist-op-den-Berg, by Atelier Kempe Thill/Daniel van Doorslaer [49], Ørestad Retirement Home in Copenhagen by JJW Arkitekter [50], New Ground Cohousing High Barnet in

London, by Pollard Thomas Edwards [51], Chapter House, Lichfield, Staffordshire | Proctor and Matthews Architects [52], Almshouse for the 21st Century in Witherford, by Watson Mann Architects [53], Community Centre in Stuttgart, by Lederer Ragnarsdottir Oei [54], Senior Dwellings in Domat/Ems, by Dietrich Schwarz [55], Kaufhaus Breuer in Eschweiler, designed by BeL [56], Senior Residence Spirgarten in Zurich, by Miller & Maranta [57,58], Tårnåsen Housing and Activity Center in Oppegård, by Kvernaas Arkitekter [59], Stadtcarré in Bad Rappenau, by ASIR Architekten [60], or Wohnfabrik Solinsieme in Sankt Gallen, designed by Archplan AG [61].

Two examples of prefabricated buildings were mentioned. The first one is Foxfields in Upton, Northampton, which was designed by Fusion Building Systems using 2D steel prefabrication [62]. The other example is Richard Onslow Court in Shrewsbury, which is the only example of a steel volume prefabrication building [63]. The project for Richard Onslow Court was carried out by M-AR. Unfortunately, the limited amount of published information did not allow for a detailed comparison of solutions in these projects. Table 1 contains eleven features that are characteristic and relevant to the construction of buildings for seniors, as identified from the literature on the subject.

By reviewing the table's cells, it is possible to determine the frequency of these features in individual projects. It is also evident that these eleven features are generally present in all the projects cited (Figure 2).

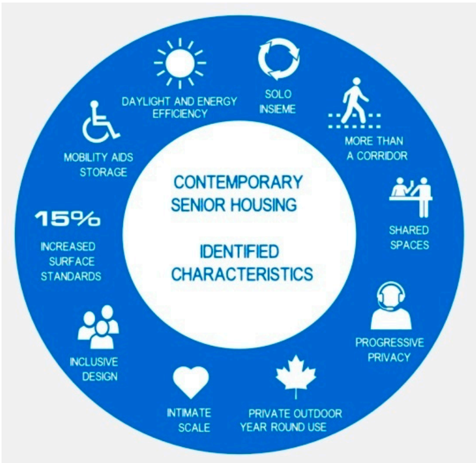


Figure 2. Contemporary senior housing—identified characteristics scheme. By authors.

1. Soloinsieme—separate but together

Soloinsieme is a word coined by conflating the Italian words 'separate' and 'together'. It illustrates the approach to shaping many cases of senior housing. Soloinsieme desires to combine the advantages of independent living with shared spaces that provide contact with other people without the need to move or leave the house [5]. Soloinsieme encompasses a wide range of spatial solutions, referring to, among other things, visual connectivity between the apartment and circulation spaces and between the apartment and the garden, circulation spaces (entrance galleries, halls, atria), private recreational spaces (balconies, loggias, terraces, and their mutual orientation and the views they offer), presence of shared spaces such as living rooms, dining rooms, communal kitchens, shared terraces and gardens. Soloinsieme applies to spaces explicitly designed for socializing and those that merely foster casual neighborhood encounters.

Table 1. Overview of leading senior housing projects—research sample (authors' elaboration).

		(1) Soloin-sieme	(2) More than a Corridor	(3) Shared Spaces	(4) Progres-sive Privacy	(5) Private Outdoor Space for Year-Round Use	(6) Intimate Scale	(7) Increased Surface Area Standard	(8) Daylight Access	(9) Inclusive Design and Process	(10) Mobility Aids Storage	(11) Energy Efficiency and Protection from Overhating
A	Heist-op-den-Berg | Atelier Kempe Thill/Daniel van Doorslaer	■	■	□	□	■	■	□	■	□	■	■
B	Ørestad Retirement Home, Copenhagen | JJW Arkitekter	■	■	■	■	■	■	■	■	□	□	■
C	New Ground Cohousing, High Barnet, London | Pollard Thomas Edwards	■	□	■	■	□	■	■	■	■	n/A	■
D	Chapter House, Lichfield, Staffordshire | Proctor and Matthews Architects	■	□	■	■	n/A	■	n/A	■	■	n/A	■
E	Almshouse for the 21st Century | Witherford Watson Mann Architects	■	■	■	■	■	□	■	■	■	■	■
F	Community Centre, Stuttgart | Lederer Ragnarsdóttir Oei	■	■	■	■	■	■	□	■	■	■	■
G	Senior Dwellings, Domat/Ems | Dietrich Schwarz	□	■	□	■	■	■	□	■	□	□	■
H	Kaufhaus Breuer, Eschweiler | BeL	■	□	■	■	■	■	■	■	■	n/A	■
I	Senior Residence Spirgarten, Zurich | Miller & Maranta	■	■	■	■	■	■	■	■	■	n/A	■
J	Tårnåsen Housing and Activity Centre, Oppegård | Kvernaas Arkitekter	■	■	■	■	■	■	□	■	■	n/A	■
K	Stadtcarré, Bad Rappenau | ASIR Architekten	■	■	■	■	■	■	■	■	■	□	■
L	Wohnfabrik Solinsieme, Sankt Gallen | Archplan AG	■	■	■	■	■	■	■	■	■	□	■
M	Richard Onslow Court, Shrewsbury | M-AR *	■	n/A	■	n/A	n/A	■	n/A	□	n/A	■	n/A
N	Foxfields, Upton, Northampton | Fusion Building Systems **	■	n/A	■	n/A	■	■	n/A	■	n/A	n/A	n/A

* 2D steel prefab; ** steel volumetric prefab. Symbols: ■—feature present; □—feature absent; n/A—adequate information not available.

2. More than a corridor

In most mainstream collective housing projects, indoor common and circulation spaces are minimized. In senior housing, these areas may be conducive to social interactions and often account for 35% or more of the indoor space, compared to 20% expected in standard housing. Corridors lacking daylight and single-aspect apartments on both sides, while the most economical, are not recommended. Better are daylit indoor galleries. Wide galleries with seating areas or at least alcoves at room entrances are preferred, as they break up the monotony of corridors and allow for personalization of the unit entrances. Such 'porches' can be furnished by residents with benches and flowerpots. Other advantages of circulation galleries are cross ventilation of units (subject to compliance with fire protection requirements) and visual contact between the private apartment and common areas. However, outdoor galleries are not recommended in Poland's climate conditions. Dead-end corridors should be avoided. Some studies note the ambiguous evaluation of courtyard layouts with O-shaped circulation; according to some sources, it can create a sense of confusion, especially for those suffering from dementia. In larger buildings, apartments can be grouped in nests, with a few entrances facing each other. Because of elderly residents' dependence on elevators, it is recommended that multi-story buildings be equipped with a minimum of two elevators in case one is out of order.

3. Shared spaces

Shared outdoor and indoor spaces relieve loneliness and promote healthy and active lifestyles. According to social psychology research, the presence of other people can significantly enhance one's performance. This is known as social facilitation and was first studied in [64]. In all but the most minor developments, residents should have access to a multifunctional shared space that offers an appropriate range of activities. The program of common spaces varies and depends on the market demand, the degree of care offered, and the size of the complex. Joint appearances include a shared kitchen and a dining room, lounge (living room with sofas), and protected terrace. In more significant buildings, there are educational spaces, a library, an IT corner, a hobby room, a fitness room, a therapy room, a hairdresser, and a spa. Depending on the concept and location, some or all of these services can also be used by non-residents. In the literature, one can find cautions against lobbies that are too spacious, hotel-like in nature; smaller, more intimate domestic spaces with a central element—a fireplace, a table, and an attractive view—are preferred. A guest apartment that can be used short-term by family or friends who visit residents might complement this area.

4. Progressive privacy

The orchestration of building spaces should filter access to its parts, guarantee privacy and security in apartments, allow residents to meet in common areas, and promote visits by residents' guests. Outdoor space should be similarly graded. The home's character should be open, inviting, intuitive, and conducive to social interaction. It is recommended to apply the principles of defensible space.

5. Private outdoor space for year-round use

Older people spend up to 70–90% of their time indoors. Mobility decreases with age, and every outing can become a challenge, so every unit should have its own outdoor space large enough to set up chairs and a table, grow plants (preferably on an elevated platform), and maneuver a wheelchair. The space should be sheltered from the wind and enable enjoying sunlight on colder days. Many analyzed projects comprised such spaces as loggias, balconies, or terraces that helped to mitigate the transition from inside to outside.

6. Intimate scale

Spatial and functional solutions should bear the characteristics of domesticity rather than institutional care and evoke a sense of calm and security. The size of the facility (number of dwelling units) is related to the adopted model of care and economic considerations: homes for residents who require permanent and, therefore, more expensive care and related additional amenities tend to be larger. Adequate design strategies should reduce the perceived scale of the building and evoke the feeling of domesticity.

Research shows that people prefer semi-closed areas, while fully closed space "arouses anxiety and a sense of claustrophobia in high-rise buildings" [65]. Also, outdoor space should be enclosed so to give physical and psychological protection. Courtyard solutions are popular: protected, secure, semi-private, functionally and visually linked to apartments, offering sun and shade, privacy, and community. A focal and space-structuring central element, such as a large tree or a pond, is desirable [66].

7. Increased surface area standard

An increase of 10–15% over the regular surface area standards of apartments considers the limited mobility of the seniors, the aids they use (crutches, walkers, rollators, wheelchairs), and the necessary maneuvering space. The higher surface standard also allows for flexible arrangement, as users' needs may change over time. According to some guidelines, the apartment layout should enable the enclosing of an additional room, which could become a bedroom for a person who permanently assists the resident or a guest room for a visiting family. According to the UK guidelines [48], a two-person apartment with one bedroom that considers seniors' needs should be 55–58 m^2, compared to 50 m^2 in the case of an apartment that does not consider seniors' needs.

8. Daylight access

As we age, our senses, including sight, deteriorate. Elderly residents need well-lit rooms, so the location, shape, size, detail, and the view from the window all play an essential role. The horizon of the mainly seated person should be taken into account. The role of the window is not only to admit daylight; they provide seniors with contact with the environment: nature and other people. However, overheating of the rooms should be avoided.

9. Inclusive design

Seniors are a group as diverse as society is diverse. This diversity and difference should be accepted. Where one design solution cannot answer everyone's needs, choices should be offered.

10. Mobility aids storage

Outside the apartment and, if possible, inside it, storage space should be provided for mobility aids, such as walkers, wheelchairs, etc. in a quantity and size reflecting the needs.

11. Energy efficiency and protection from overheating

In addition to meeting energy efficiency requirements, the building should be protected from overheating through passive solutions such as external blinds, shutters, awnings, green roofs, deciduous plantings, and roof vents. It is assumed that for the elderly, overheating poses a greater risk than cold.

4.2. Dwelling Units for the Elderly as "Building Blocks"

The requirements of the NCBR call were used to create dwelling units of two types, which were then considered 'building blocks' for the formation of entire buildings for the elderly. On the one hand, these 'building blocks' should allow for 3D prefabrication using the study funder's technology. On the other hand, they should embody eleven features identified by the authors and discussed above. The list of features for the design of the modules included No. 5, which was the provision of private outdoor space for year-round use. This was achieved through the incorporation of deep loggias. Another important feature was No. 7, which involved providing larger areas than what ergonomics alone would suggest, to ensure flexibility in arrangement. To connect two adjacent modules intended to form a single apartment, a bracing solution of a steel structure was provided in the walls without diagonal stays. Adequate access to light was ensured by installing a calculated area of windows immediately in the modules, following feature No. 8. Each apartment also had an area for storing mobility aids, including an expansive wardrobe closet provided in the entrance area (feature No. 10). As 3D prefabrication assumes ready-to-assemble modules, thermal comfort issues in the form of adequate thermal insulation and passive blinds were also taken care of, following feature No. 11.

The resultant dwelling units consist of two 3D modules with a transport width of 430 cm (the module housing the living area of the apartment, including the loggia) and 330 cm (the module housing the night area of the apartment). The areas of the dwelling units created from the modules thus designed were 39.2 m^2 and 49.3 m^2 (Figure 3).

(**a**) (**b**)

Figure 3. Dwelling unit plans created and evaluated by authors: (**a**) dwelling unit for one, unit area 39.2 m^2 and a balcony of 7 m^2; (**b**) dwelling unit for two, unit area 49.3 m^2 and a balcony of 7 m^2.

The authors used expert methods to evaluate housing unit modules for repeated use, focusing on modularity/prefabrication, day/night zoning, and wheelchair accessibility to furniture and equipment. When evaluating a design variant, the formal and technical qualities of it were considered. These qualities included appearance, compliance with regulations, functional utility program, ergonomics, and energy efficiency. Based on these, different sets of qualitative characteristics are derived: functional, economic, behavioral and technical. The evaluation involved a checklist of design quality ratings (Figure 4).

4.3. Alternative Proposals of Collective Senior Housing Buildings

Although there is a limited number of dwelling units, there is a greater variety of modules on the production side due to the more complimentary and varied design of circulation spaces, which have numerous auxiliary functions in senior housing.

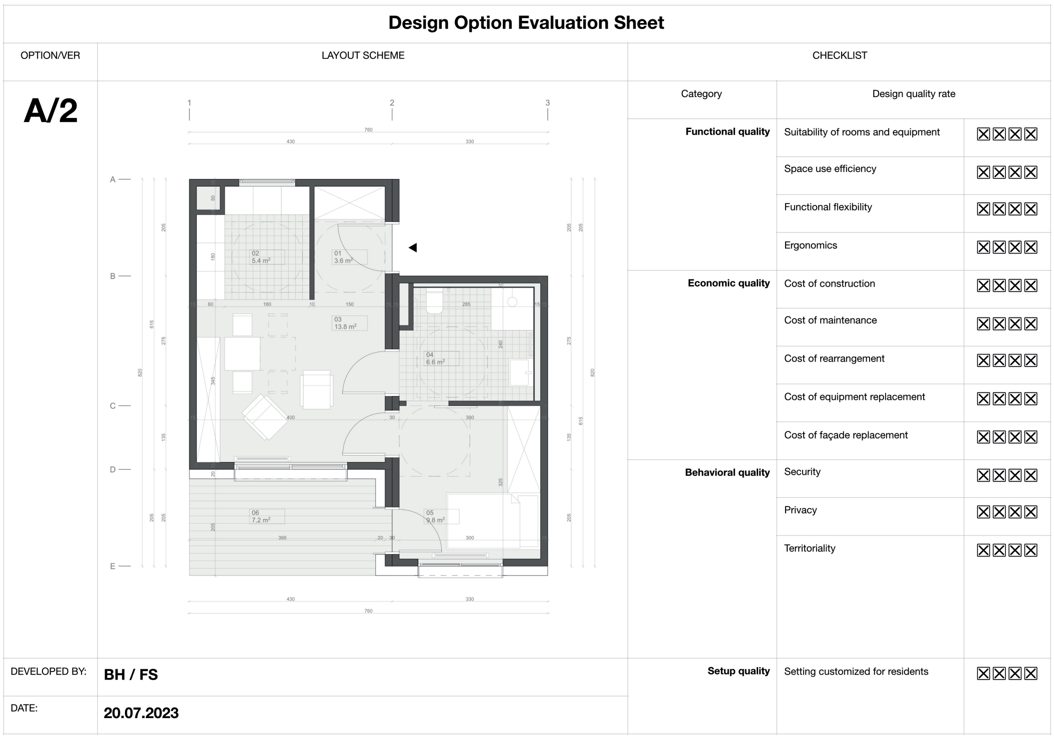


Figure 4. The design option evaluation sheet, including a layout scheme and checklist of design quality ratings, as discussed in the text—authors' elaboration.

A modular system can be understood as a well-thought-out range of standard parts arranged according to size and span so that every possible design and combination of building elements can be built [35]. This approach makes it possible to achieve the most extensive number of combinations with the smallest number of different parts (here reduced to a primary three). In this way, the design process approaches Leibnitz's combinatorics [67].

The authors developed three different building proposals based on the building blocks created. They tested a variety of functional-spatial layouts. Each variant has a residential part, a two-story block characterized by the regularity of form and rhythm, and a shared part, a single-story pavilion with a more free-form design that can be enlarged depending on the utility program. The authors have implemented various postulates for the characteristics of an appropriate senior architecture in these configurations. These include an intimate scale, circulation surfaces that serve both functional and socializing purposes, transparency, and compactness of interiors in accordance with the principles of universal architecture.

In the second stage of the evaluation, the authors evaluated measurable building parameters compiled from the same modules in different configurations (Figures 5–7). The evaluation criteria included land demand, number of modules, usable area to communication area ratio, quality of social spaces, facade composition and aesthetics, entrance area quality, and accessibility. A tabular matrix was created to assess various factors and their mutual influence. Four members of the research team evaluated the variants, and two external consultants were also consulted. The results are presented in Figure 8. In the green boxes, the researchers rated the impact of a criterion from a row on a benchmark from a column on a scale of −4 to 4, where −4 represents a significant negative impact and 4 represents a substantial positive impact. In the yellow boxes, the researchers rated the degree to which a variant (from the row) meets the criterion (from the column) on a scale of 0 to 4, where 0 represents that the variant does not meet the criterion, and 4 represents that the variant meets the criterion to a substantial degree. Finally, the weights of the criteria were entered in the blue boxes based on the maximum number of points possible in the evaluation by the competition organizing institution (NCBR).

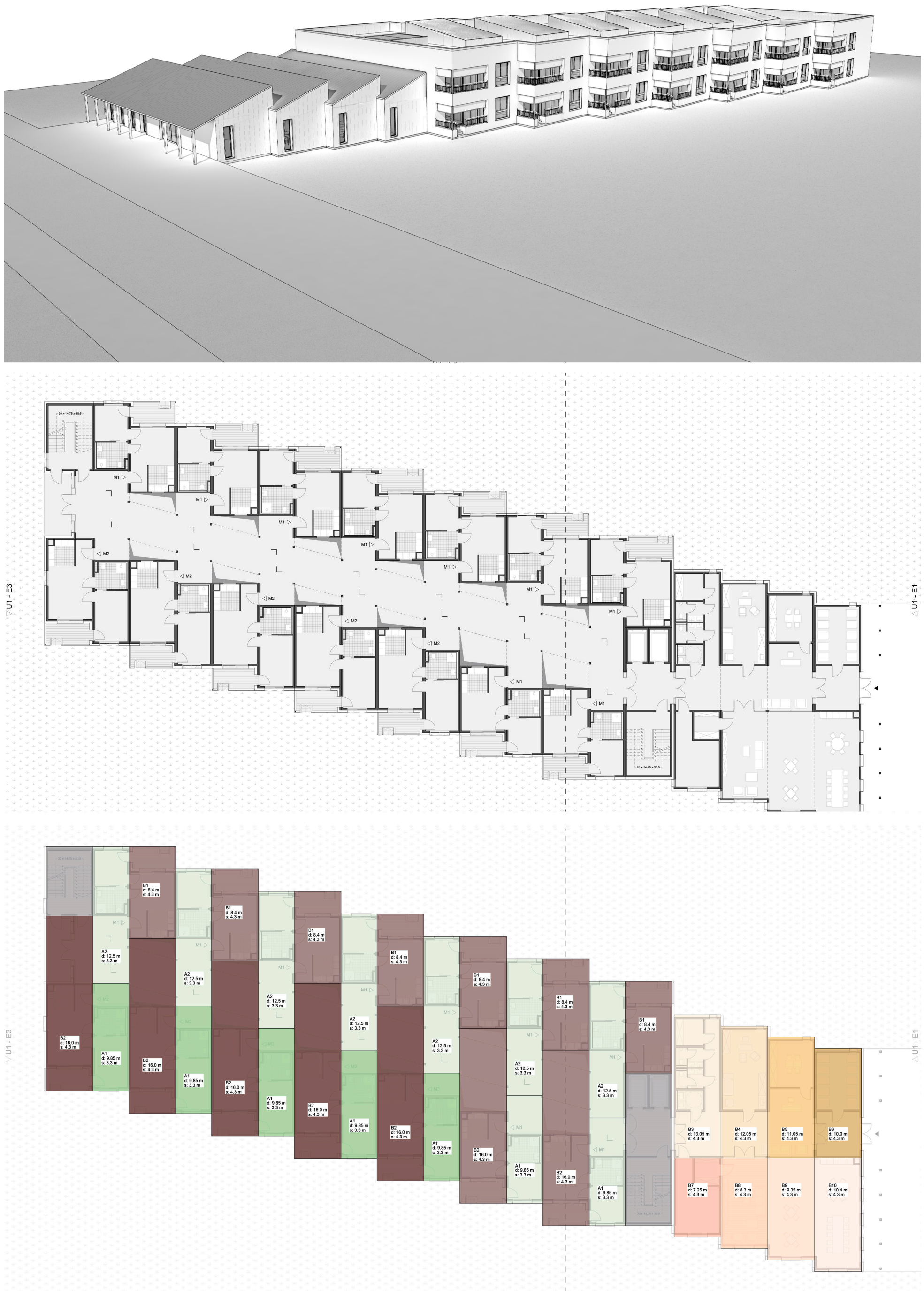


Figure 5. The first proposal of grouping dwelling modules is linear in the form of a sawtooth. Each color represents a specific type of 3D module that has the same dimensions and equipment. By authors.

Using Space Syntax testing, the authors analyzed the visibility field and predicted user behavior to evaluate different design options. Thus, quantifying human visual comfort and visibility in 2D and 3D while incorporating the movement pattern allowed the evaluation based on the human visual perspective simulation. The test only covers visibility and not physical accessibility or barriers to movement. Openings have been placed in the center of the corridor, which, despite being an obstacle at the floor level, allows visual contact with people moving along the corridor on the lower floor. These wells also allow natural light to enter the building through skylights (see Figure 7).

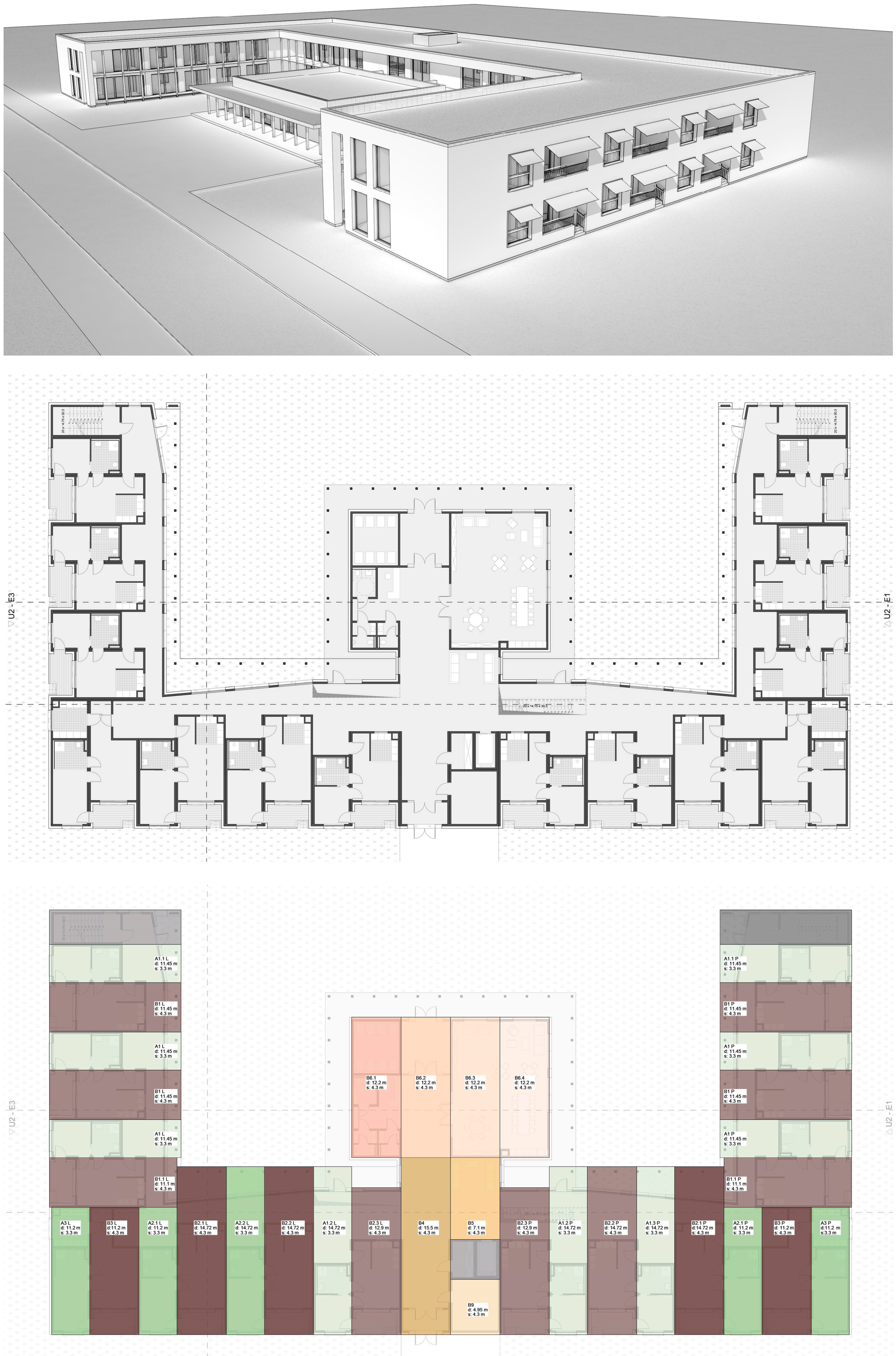


Figure 6. The second proposal is a grouping of dwelling modules in a U-shape with an inner courtyard. Each color represents a specific type of 3D module that has the same dimensions and equipment. By authors.

The degree of mutual visibility confidently indicates social interaction levels. Points with high "co-visibility" (marked in red) both see and are seen alongside many other locations. Points with low visibility (marked in blue) are both seen and are seen from fewer other locations. A high value is correct for public spaces, while a lower value is correct for private/semi-private residential units (Figures 9 and 10).

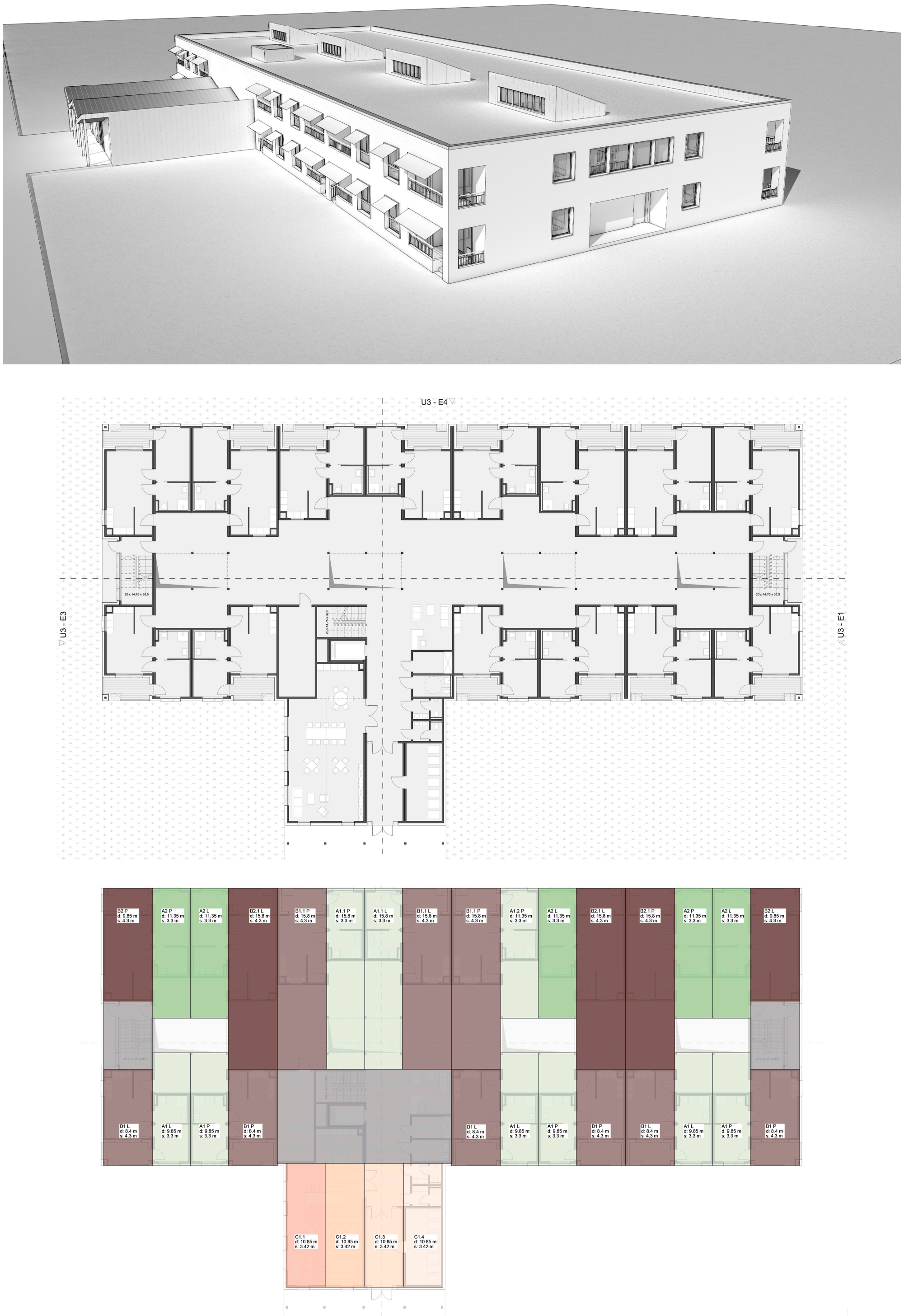


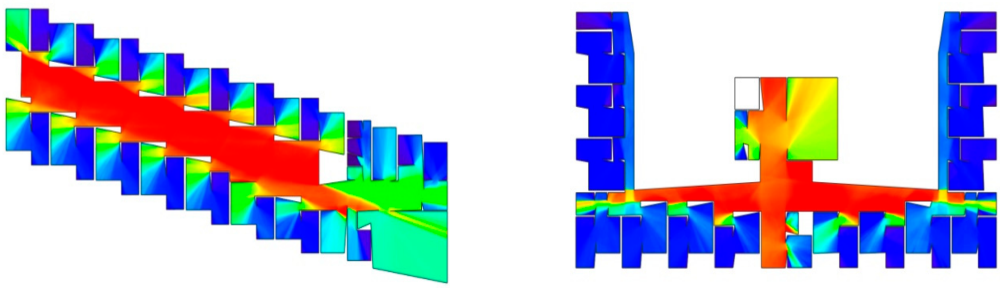
Figure 7. The third proposal of grouping dwelling modules is linear rectangular with deep tract. Each color represents a specific type of 3D module that has the same dimensions and equipment. By authors.

Three site plan proposals were made accordingly for three module configurations. Each includes parking, bicycle storage, green areas, and waste storage. The buildings are two floors and under 12 m high. A public road and fire road run along the longer side of the buildings. However, the 4000 sqm plot size mentioned in the NCBR call proved to be certainly inadequate. A sufficient area of green recreational space is required to ensure the quality of space and comfort of users, especially senior housing.

	TOTAL COSTS	ENERGY BALANCE	ENERGY CONSUMPTION	WATER BALANCE	CARBON FOOTPRINT	RECYCLING OF BUILDING MATERIALS	COMMERCIALIZATION REVENUE	COMMERCIALIZATION OF SUBSIDIARY TECHNOLOGIES REVENUE	PRICE FOR IMPLEMENTATION OF STAGE I	PRICE FOR CONSTRUCTION STAGE II	PRICE FOR CONSTRUCTION STAGE III	ENERGY STORAGE	WASTEWATER TREATMENT/GREYWATER	THERMAL COMFORT	PROPOSED TECHNOLOGY	CONCEPTUAL DESIGN OF THE DEMONSTRATOR	INNOVATIVE SOLUTIONS	PREFABRICATION / MODULARITY
TOTAL COSTS	3	−1	2	2	2	1	−2	−2	−1	−2	−4	1	1	1	−1	−2	−2	−2
ENERGY BALANCE	−2	4	3	0	−1	1	2	3	0	0	−2	3	0	4	1	1	4	1
ENERGY CONSUMPTION	−2	4	3	0	−1	0	−1	−2	0	0	−2	3	0	2	1	1	3	1
WATER BALANCE	−1	0	0	2	0	0	1	1	0	0	−1	0	2	0	1	1	2	0
CARBON FOOTPRINT	−1	−1	−1	0	2	4	0	0	0	0	−2	2	0	1	1	1	3	2
RECYCLING OF BUILDING MATERIALS	−1	0	0	0	4	2	0	0	0	0	0	0	0	0	1	0	0	0
COMMERCIALIZATION REVENUE	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
COMMERCIALIZATION OF SUBSIDIARY TECHNOLOGIES	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
PRICE FOR IMPLEMENTATION OF STAGE I	−1	3	3	2	1	1	1	1	1	0	0	1	1	1	1	3	2	1
PRICE FOR CONSTRUCTION STAGE II	−1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	−4	−3	−2
PRICE FOR CONSTRUCTION STAGE III	−4	−1	−1	−1	0	1	−3	−3	0	−2	1	−1	−1	−1	−2	0	−3	−3
ENERGY STORAGE	−1	4	4	0	4	3	4	3	−1	−1	−2	2	0	4	2	1	4	2
WASTEWATER TREATMENT/GREYWATER	−1	0	0	3	−1	0	0	0	0	0	−1	0	2	0	0	1	2	0
THERMAL COMFORT	−2	−3	−4	0	−3	−1	1	1	0	0	−2	3	0	2	−2	1	3	3
PROPOSED TECHNOLOGY	−1	1	1	0	−2	4	4	4	2	2	−2	4	0	2	4	4	4	4
CONCEPTUAL DESIGN OF THE DEMONSTRATOR	1	1	1	0	3	2	0	0	0	0	0	2	3	4	4	4	4	4
INNOVATIVE SOLUTIONS	1	4	4	3	1	1	4	4	1	1	1	4	4	2	3	4	3	4
PREFABRICATION / MODULARITY	4	1	1	0	−2	4	4	2	0	0	−2	0	0	−1	4	4	4	2
ENERGY STORAGE	−2	4	4	0	1	1	4	4	0	0	−1	0	0	3	2	2	4	1
SITE AND LANDSCAPING	−2	0	0	0	0	1	0	0	0	0	−2	0	2	0	0	0	1	0
APARTMENTS ZONING DAY/NIGHT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CIRCULATION SURFACE RATIO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	−2	0	0	−2
POSSIBILITY OF REMOTE WORK	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ACCESS TO FURNITURE AND EQUIPMENT BY WHEELCHAIR	−2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	−2
QUALITY OF INTERNAL SHARED SPACES	−2	0	0	0	0	0	0	0	0	0	−2	0	0	0	0	0	0	0
FACADE LAYOUT	−3	0	0	0	0	0	0	0	0	0	−2	0	0	0	2	2	3	2
DIVERSITY OF FACADES	−2	0	0	0	−3	−3	0	0	0	0	−2	0	0	0	0	0	0	−3
QUALITY OF THE ENTRANCE ACCESS ZONE	−2	0	0	0	0	0	0	0	0	0	−2	0	0	0	0	0	0	0
DIVERSITY OF URBAN FURNITURE ELEMENTS	−2	0	0	0	0	1	0	0	0	0	−2	0	0	0	0	0	0	0
INCLUSIVE SPORTS AND LEISURE SPACES	−2	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0	0
QUALITY OF SEMI–PRIVATE SPACE PRODUCED	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SOCIAL SURVEILLANCE/CO–VISIBILITY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DISTANCE OF SOCIAL SPACES FROM THE ENTRANCE AREA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DISTANCE OF THE ENTRANCE TO THE PROPERTY BORDER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
THE POSSIBILITY OF INTRODUCING A FIRE ROAD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BASELINE	2	1	1	3	0	2	2	4	3	4	4	2	0	0	3	3	2	3
OPTION 1	4	4	4	4	2	3	3	4	3	4	3	4	3	3	4	4	4	4
OPTION 2	3	4	4	4	2	3	3	4	3	4	3	4	3	3	4	4	4	4
OPTION 3	2	4	4	4	1	2	3	4	3	4	2	4	3	3	2	3	3	3

	ENERGY STORAGE	SITE AND LANDSCAPING	APARTMENTS ZONING DAY/NIGHT	CIRCULATION SURFACE RATIO	POSSIBILITY OF REMOTE WORK	ACCESS TO FURNITURE AND EQUIPMENT BY WHEELCHAIR	QUALITY OF INTERNAL SHARED SPACES	FACADE LAYOUT	DIVERSITY OF FACADES	QUALITY OF THE ENTRANCE ACCESS ZONE	DIVERSITY OF URBAN FURNITURE ELEMENTS	INCLUSIVE SPORTS AND LEISURE SPACES	QUALITY OF SEMI–PRIVATE SPACE PRODUCED	SOCIAL SURVEILLANCE/CO–VISIBILITY	DISTANCE OF SOCIAL SPACES FROM THE ENTRANCE AREA	DISTANCE OF THE ENTRANCE TO THE PROPERTY BORDER	THE POSSIBILITY OF INTRODUCING A FIRE ROAD
TOTAL COSTS	1	−1	−1	0	−1	−2	−2	−2	−2	−2	−2	−1	−1	0	0	0	0
ENERGY BALANCE	3	0	0	0	0	0	0	−2	−2	0	0	0	0	0	0	0	0
ENERGY CONSUMPTION	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WATER BALANCE	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
CARBON FOOTPRINT	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
RECYCLING OF BUILDING MATERIALS	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
COMMERCIALIZATION REVENUE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
COMMERCIALIZATION OF SUBSIDIARY TECHNOLOGIES	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PRICE FOR IMPLEMENTATION OF STAGE I	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
PRICE FOR CONSTRUCTION STAGE II	0	−2	0	0	0	0	0	0	0	−1	−1	−1	−1	−1	−1	−1	0
PRICE FOR CONSTRUCTION STAGE III	−1	−2	0	0	0	−3	−4	−4	−4	−2	−2	−1	0	0	0	0	0
ENERGY STORAGE	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WASTEWATER TREATMENT/GREYWATER	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
THERMAL COMFORT	3	0	0	0	0	0	0	−1	−1	0	0	0	0	0	0	0	0
PROPOSED TECHNOLOGY	4	1	−3	−1	−2	−1	0	−3	−4	0	0	0	0	0	0	0	0
CONCEPTUAL DESIGN OF THE DEMONSTRATOR	2	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0
INNOVATIVE SOLUTIONS	4	4	1	1	1	1	1	4	4	2	2	2	1	2	1	1	0
PREFABRICATION / MODULARITY	0	0	−2	0	−1	0	0	−3	−3	0	0	0	0	0	0	0	0
ENERGY STORAGE	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SITE AND LANDSCAPING	0	2	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0
APARTMENTS ZONING DAY/NIGHT	0	−3	1	0	2	−2	0	−2	−2	0	0	0	0	0	0	0	0
CIRCULATION SURFACE RATIO	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
POSSIBILITY OF REMOTE WORK	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
ACCESS TO FURNITURE AND EQUIPMENT BY WHEELCHAIR	0	2	−3	0	−2	1	−1	0	0	2	2	3	2	0	2	2	0
QUALITY OF INTERNAL SHARED SPACES	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
FACADE LAYOUT	0	0	−2	0	0	0	1	1	2	2	0	0	1	0	0	0	0
DIVERSITY OF FACADES	0	0	0	0	0	0	0	3	1	3	0	0	0	0	0	0	0
QUALITY OF THE ENTRANCE ACCESS ZONE	0	1	0	−1	0	0	3	1	1	1	2	0	2	2	2	2	0
DIVERSITY OF URBAN FURNITURE ELEMENTS	0	3	0	0	0	0	0	0	0	1	1	2	2	0	0	0	0
INCLUSIVE SPORTS AND LEISURE SPACES	0	2	0	0	0	0	0	0	0	0	1	1	2	2	0	0	0
QUALITY OF SEMI–PRIVATE SPACE PRODUCED	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SOCIAL SURVEILLANCE/CO–VISIBILITY	0	1	0	0	0	0	0	2	2	0	0	0	0	1	2	2	0
DISTANCE OF SOCIAL SPACES FROM THE ENTRANCE AREA	0	2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
DISTANCE OF THE ENTRANCE TO THE PROPERTY BORDER	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0
THE POSSIBILITY OF INTRODUCING A FIRE ROAD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BASELINE	2	2	2	3	3	1	3	1	0	1	2	2	2	2	2	4	0
OPTION 1	4	4	3	4	4	2	2	4	4	4	3	3	4	3	2	4	2
OPTION 2	4	3	3	4	4	2	2	4	4	2	3	4	3	4	4	2	0
OPTION 3	4	4	4	3	4	3	2	3	3	4	3	3	4	3	2	4	2

Figure 8. The authors compile a tabular matrix to evaluate each option—explanations in the text.



(**a**) (**b**)

Figure 9. Visualizations of the isovist study allow for the comparison of two design variants. The factor values are represented by a color scale ranging from red (highest) to dark blue (lowest). The different availability of circulation creates a different framework of social space, marked in red: (**a**) linear sawtooth layout; (**b**) central U-shaped layout. By authors.

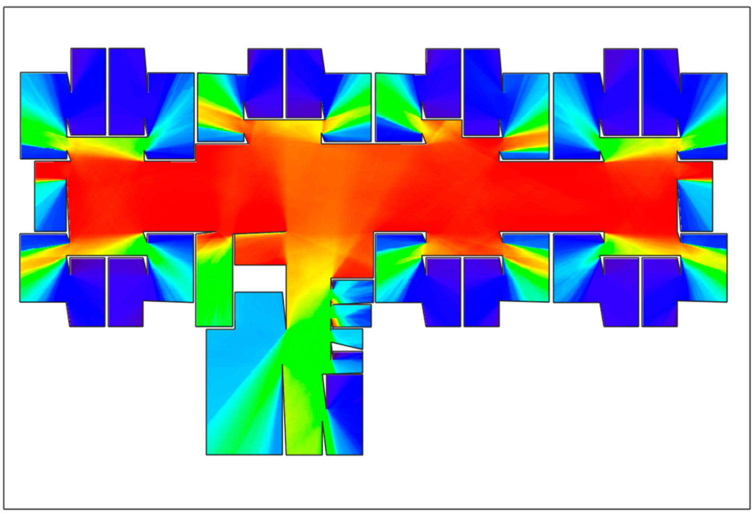


Figure 10. Rectangular layout isovist study. The factor values are represented by a color scale ranging from red (highest) to dark blue (lowest). High Co-visibility measures are in the shared spaces/circulation. By authors.

5. Discussion

The research's starting point was that senior housing presents a promising opportunity for volumetric modular prefabrication. Housing for older adults is similar to multifamily housing and hospitality (e.g., hotels or dormitories). The repetitive nature of the housing units in these projects and the possibility of turnkey finishing and furnishing under controlled factory conditions make their 3D prefabrication attractive.

However, there are distinct differences between senior housing and other dwelling types. The study identified eleven constitutive elements of a suitable architecture for older adults.

The living units are the main component of senior buildings, and they should meet older adults' physical and mental needs. The living unit's size is crucial, including width in clear and internal layout. As mobility declines, seniors may need to use assistive devices like crutches, walkers, and wheelchairs. This means that some characteristic dimensions in a senior housing unit should be larger than in houses that do not consider universal design requirements. The width of corridors must allow a wheelchair to turn to perform activities, and the size of kitchens, bathrooms, and bed areas should accommodate wheelchair access. Some furniture and utensils, such as adjustable beds, toilets, sinks, shower trays, and tables, should be oversized. The configuration of these items must allow access without interfering with walkers or wheelchairs. A comfortable senior citizen apartment should be slightly larger than an apartment with the same program that does not consider the needs of seniors and people with disabilities. Optimally designed for young, fully mobile people, narrow apartment modules (such as in dormitories or budget hotels) may not suit the needs of the elderly. Loggias, balconies, or terraces should not be minimal, as they provide easy access to nature for people with limited mobility. It remains a challenge to eliminate thermal bridges at the joints between these external spaces and the heated volume. Many of the needs of seniors relate to detailed solutions inside the apartment. Implementing these will be possible when using volumetric modular prefabrication, provided that the importance of these aspects is realized and considered in the design. The appropriate size and location of windows and doors, the presence of a secluded, covered but sunny loggia, terrace, or balcony, and the leveled thresholds should be considered at the design stage. The same applies to providing appropriate furniture and sanitary facilities and ensuring thermal and acoustic comfort.

The review of the best housing solutions aimed at seniors conducted during this research and development work has proven that the solutions of the shared parts in the building are no less important than the housing unit itself. Common spaces allow seniors to establish and maintain social contacts, fulfilling their psychological and social needs. Shared living rooms, kitchenettes, and terraces are essential spaces in circulation spaces and at the interface between the private and the public domain. These spaces should be well-lit, provide varied views from the inside and outside, and have a home-like character. Circulation spaces should not be minimal, as they perform essential social functions and are a substitute for the street for less mobile residents. The challenge for 3D modular technology is the public/shared zone of senior housing facilities, where open, continuous space is preferred. Other technologies may appear required because of larger spans and increased room heights. Due to increased fire safety requirements in premises for persons with reduced mobility, vertical circulation cores should be constructed with 2D–3D reinforced concrete prefabrication or on-site construction.

6. Conclusions

The study showed that constructing a one- or two-person housing unit for older people with 3D modules is possible. Regarding volumetric prefabrication, one housing unit would likely consist of two 3D modules adjacent to each other with their longer sides. Their width is critical. Designers and builders must balance the opposing demands of transportation economics (narrower span modules) and the mobility requirements of aging residents (wider span modules).

The study proved that a single housing unit may embody many features of suitable architecture for older adults. They may refer to sequencing spaces in such a way that both privacy and togetherness can be experienced and their degree controlled by the residents of any unit; forming the unit's doorstep to promote socializing in circulation spaces; folding the facade to create nooks and recesses for loggias or balconies, thus mitigating the transition between indoor and outdoor space and providing protected outdoor space for year-round use; designing windows for daylight and views and controlling sunlight; and providing units' layout that enable reconfiguration to address various and changing needs of the residents.

On the other hand, the study demonstrated that the most economical form of 3D prefabrication—that is, an extended 3D module that houses two rooms on either end, separated by a corridor in the middle—is not recommended for senior housing as it results in monotonous, likely dark circulation space. Moreover, in contrast to student dormitories or hotel buildings, one single 3D module of limited width cannot successfully accommodate a complete dwelling unit for older people due to increased room dimension needs. Both these facts pose challenges in the 3D prefabrication of senior buildings.

Despite that, the study demonstrated the feasibility of forming differentiated layouts of senior housing buildings. The study tested three morphologically distinct variants built with two-module dwelling units developed previously.

In terms of shaping the architectural form, the repetition of dwelling modules makes it possible to achieve rhythmic masses and façade expression.

On the other hand, this repetitiveness can result in a monotonous and institutional look. As a natural feature of modular construction is to make the most of the advantages of the technology, one should be wary of a primitive form, far from the associations with a house or an intimate collective housing. Loggias allow residents to be outside and simultaneously soften the boundary between the building and the surroundings and give the building a residential, domestic character. Another chance to break the monotony is to form the common parts of the building freely, in contrast to the repetitive dwelling part.

The NCBR's too strict requirements considerably limited the design options. For instance, the strict distribution of the apartments (18 one-person and 10 two-person units) eliminated some promising building layouts. In future calls of this nature, some flexibility in the number of units of each type would be beneficial. Moreover, despite the importance of outdoor spaces for senior housing projects, we could not fully address it in the study, as the call concerned an undefined site. Similarly, not knowing the location and the distance from the off-site production facility, we could not take the aspect of transportation into consideration. As there are many manufacturers in the 3D prefabrication industry, we could only take into account the technology of one of them. Closer consultancy with the funder (technology owner) would be helpful at the development stage.

The application of volumetric prefabrication in senior housing can be seen as the interconnected system aimed on cost-effectiveness (linked with seriation) on the one hand, and the endeavor for complexity (linked with the richness of experiences of living) on the other hand. Volumetric prefabrication of senior housing may contribute to the increased cost-effectiveness through shorter investment process, shorter construction time, and, thanks to possibility of dismantling and relocating when the demand changes, to a quicker response to social and market needs. The technology may be particularly suitable for extending the existing facilities, as off-site production minimizes the period of nuisances on site. The study responds to the needs of the aging, fragile population by providing energy-efficient, low maintenance compact homes for independent living and relieving loneliness. Eventually, it contributes to the progression in the prefab construction industry, widening the range of volumetric prefabrication areas.

Future research may cover a wider range of potential avenues for further investigation and explore the many aspects of the living of the elderly in homes constructed with volumetric prefabrication. An area of research that shows a lot of promise is the study of the configuration relationships between individual system elements, such as individual modules and their various groups. This study can be conducted using the space syntax, and exploring this method is a step towards developing algorithms that can be used to plot generative architectures. The algorithms would consider the most efficient configurational topologies and verify them through real-time simulations. Further in-depth research is required to explore this area in detail.

As the next stage, participatory research is envisaged, relating to users' subjective feelings and preferences concerning the finished reference building. Therefore, the next preliminary step will be an evaluation from the users' point of view under the P.O.E. technique (Post Occupancy Evaluation).

Author Contributions: Conceptualization, B.H. and F.S.; methodology, B.H. and F.S.; software, K.W. and F.S.; validation, B.H. and F.S.; formal analysis, B.H. and F.S.; investigation, B.H., F.S. and K.W.; resources, B.H., F.S., K.W. and E.W.-S.; data curation, B.H. and F.S.; writing—original draft preparation, B.H. and F.S.; writing—review and editing, B.H. and F.S.; visualization, K.W.; supervision, B.H. and F.S.; project administration, B.H.; funding acquisition, E.W.-S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by DMDmodular sp. z o.o., grant number A-09/32/2021/P. Open access for this publication has been supported by the Faculty of Architecture at Cracow University of Technology.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Statista. 2023. Available online: https://www.statista.com/topics/769/demography (accessed on 30 January 2024).
2. Population Projection 2023–2060. Available online: https://stat.gov.pl/en/topics/population/population-projection/population-projection-20232060,4,1.html (accessed on 30 January 2024).
3. Pawlitschko, R. Growing Old in One's Own Neighbourhood—New Housing Forms for Old Age. *Detail Rev. Archit. Hous. Sr.* **2017**, *3*, 10–16.
4. Cieśla, A.; Iwański, R. *Wyzwanie dla Warszawy: Mieszkalnictwo Seniorów*; Fundacja Inicjatyw Aktywnych Go Silver: Warszawa, Poland, 2017.
5. Park, J.; Porteus, J. *Age-Friendly Housing: Future Design for Older People*; RIBA Publishing: Great Britain, UK, 2018.
6. Das, Y.; Chapman, J. *Silver Hues: Building Age-Ready Cities*; © World Bank: Washington, DC, USA, 2022.
7. Ebner, P. Integrated living. In *Housing for People of All Ages: Flexible, Unrestricted, Senior-Friendly*; Schittich, C., Ed.; Insitut für International Architektur-Dokumentation GmbH & Co.: München, Germany, 2007.
8. Ji, T.-T.; Wei, H.-H.; Sun, Y.; Seo, J.; Chen, J.-H. An Explorative Study of the Political, Economic, and Social Factors Influencing the Development of Senior Housing: A Case Study of Hong Kong. *Buildings* **2023**, *13*, 617. [CrossRef]
9. King, D.; Covin, J.; Hegarty, W. Complementary Resources and the Exploitation of Technological Innovations. *Manag. Fac. Res. Publ.* **2003**, *29*, 589–606. [CrossRef]
10. Marriott's Senior Living Communities: Meeting the Need of Older Americans for Housing Options—By Kathleen Tindell (HSMAI Marketing Review). Available online: https://www.hospitalitynet.org/editorial/4011067.html (accessed on 30 January 2024).
11. Nelson, M.K. Skender Hopes to Make Modular Construction Mainstream in Senior Living, Senior Housing News. 2018. Available online: https://seniorhousingnews.com/2018/08/05/skender-hopes-make-modular-construction-mainstream-senior-living (accessed on 30 January 2024).
12. Brewer, J. Ikea Is Developing Homes for Elderly People with Disabilities and Dementia. 2019. Available online: https://www.itsnicethat.com/news/ikea-silviabo-skanska-affordable-modular-homes-for-elderly-with-disabilities-and-dementia-200819 (accessed on 30 January 2024).
13. Conklin, E. IKEA and the Queen of Sweden Update the Retirement Home for Dementia, The Architect's Newspaper. 2019. Available online: https://www.archpaper.com/2019/08/ikea-and-sweden-queen-retirement-home (accessed on 30 January 2024).
14. Available online: https://www.gov.pl/web/ncbr/budownictwo-efektywne-energetycznie-i-procesowo (accessed on 30 January 2024).

15. Available online: https://www.gov.pl/web/ncbr/ncbr-stawia-na-budownictwo-spoleczne-dla-seniorow (accessed on 30 January 2024).
16. Bayliss, S.; Bergin, R. *The Modular Housing Handbook*; RIBA Publishing: London, UK, 2020.
17. Bertram, N.; Fuchs, S.; Mischke, J.; Palter, R.; Strube, G.; Woetzel, J. *Modular Construction: From Projects to Products*; McKinsey & Company: New York, NY, USA, 2019.
18. Goldsmith, S.; Architectural Association (Great Britain) School of Architecture. *Designing for the Disabled: A Manual of Technical Information*; Royal Institute of British Architects, Technical Information Service: London, UK, 1963.
19. Mace, R.; Hardie, G.; Place, J. *Accessible Environments toward Universal Design*; Center for Universal Design: Raleigh, NC, USA, 1991.
20. Advisory Committee on Accessibility (ACA) Access Design Subcommittee. Building Accessible and Inclusive Environments. In *Universal Design Handbook*; The City of Calgary Community & Neighbourhood Services (CNS) Social Policy & Planning Division: Calgary, AB, Canada, 2010.
21. Baig, Z.; Nandal, N. Housing for the Elderly. *Ann. Rom. Soc. Cell Biol.* **2020**, *24*, 392–426.
22. Feddersen, E.; Lüdtke, I. Living for the Elderly. In *A Design Manual, 2nd and Revised ed.*; Birkhäuser: Basel, Switzerland, 2018.
23. Luciano, A.; Pascale, F.; Polverino, F.; Pooley, A. Measuring Age-Friendly Housing: A Framework. *Sustainability* **2020**, *12*, 848. [CrossRef]
24. Ng, A.W.; Leung, T.C.H.; Tsang, A.K.T. Social Enterprise for Elderly Housing: Policy for Accountability and Public-Private Responsible Financing. *J. Popul. Ageing* **2020**, *13*, 365–384. [CrossRef]
25. Hui, E.C.M.; Wong, F.K.W.; Chung, K.W.; Lau, K.Y. Housing affordability, preferences and expectations of elderly with government intervention. *Habitat Int.* **2014**, *43*, 11–21. [CrossRef]
26. Bao, H.; Meng, C. Loss Aversion and Housing Studies. *J. Real Estate Lit.* **2017**, *25*, 49. [CrossRef]
27. Ma, Y.; Xu, W. How Does the Intelligent Monitoring System Influence the Sense of Security of the Elderly in Home Care? A Case Study of the Hubin Community in Ningde City. *Buildings* **2023**, *13*, 1255. [CrossRef]
28. Lee, J.K.; Shin, J.; Lee, Y. Circulation analysis of design alternatives for elderly housing unit allocation using building information modelling—Enabled indoor walkability index. *Indoor Built Environ.* **2020**, *29*, 355–371. [CrossRef]
29. Mariana, Y.; Triwardhani, A.J.; Djimantoro, M.I. The study of a space configuration using space syntax analysis Case study: An elderly housing. *IOP Conf. Ser. Earth Environ. Sci.* **2017**, *109*, 012048. [CrossRef]
30. Zhang, Y.; Wu, Z.; Wu, Z.; Liu, Y.; Yang, Z. Using Space Syntax in Close Interaction Analysis between the Elderly: Towards a Healthier Urban Environment. *Buildings* **2023**, *13*, 1456. [CrossRef]
31. Nourian, P. Configraphics: Graph Theoretical Methods for Design and Analysis of Spatial Configurations. *Archit. Built Environ.* **2016**, *14*, 348. [CrossRef]
32. Wu, Z.; Sober, R. Design of Modular Housing Suitable for the Elderly. *Int. Res. J. Eng. Technol.* **2020**, *7*, 1800–1808.
33. Choi, C.S.; Chung, J.H.; Kim, B.S.; Kim, J. A Study on Modular-Based Prototypes for the Elderly Housing. *Adv. Sci. Lett.* **2017**, *23*, 10440–10444. [CrossRef]
34. Janahi, H.Y. Social Wellbeing and the Residential Environment: The Influence of Design on Inhabitants' Wellbeing in Doha. Available online: https://orca.cardiff.ac.uk/id/eprint/152276/1/Janahi%20H%20Final%20Thesis.pdf (accessed on 30 January 2024).
35. Moewes, G. Kastenbau oder Baukasten? Gesetzmässigkeiten des Systembaues am Beispiel des Brockhouse-Systems, IB Industrialisierung des Bauens, Essen 5/71. Available online: https://www.guenthermoewes.de/pdf/20-Moewes-Kastenbau-oder-Baukasten.pdf (accessed on 30 January 2024).
36. Hartson, R.; Pardha, P. Chapter 13—Bottom-Up Versus Top-Down Design. In *The UX Book*, 2nd ed.; Morgan Kaufmann: Cambridge, MA, USA, 2019; pp. 279–291. ISBN 9780128053423. [CrossRef]
37. Groat, L.N.; Wang, D. *Architectural Research Methods*, 2nd ed.; Wiley: Hoboken, NJ, USA, 2013.
38. Niezabitowska, E.D. *Research Methods and Techniques in Architecture*; Routledge: London, UK, 2018.
39. Clipson, C. Simulation for Planning and Design. A Review of Strategy and Technique. In *Environmental Simulation*; Marans, R.W., Stokols, D., Eds.; Springer Science + Business Media: New York, NY, USA, 1993; pp. 23–57.
40. Hunt, M.E. Environmental Simulation Research for an Aging Society. Familiarizing Older People with the Unknown. In *Environmental Simulation*; Marans, R.W., Stokols, D., Eds.; Springer Science + Business Media: New York, NY, USA, 1993; pp. 87–112.
41. Turner, A.; Penn, A. Encoding Natural Movement as an Agent-Based System: An Investigation into Human Pedestrian Behaviour in the Built Environment. *Environ. Plan. B* **2002**, *29*, 473–490. [CrossRef]
42. Benedikt, M. To Take Hold of Space: Isovists and Isovist Fields. *Environ. Plan. B* **1979**, *6*, 47–65. [CrossRef]
43. Ostwald, M.; Dawes, M. Using Isovists to Analyse Architecture. *Int. J. Constr. Environ.* **2013**, *3*, 85–106. [CrossRef]
44. Othman, F.; Yusoff, Z.M.; Rasam, A.R.A. Isovist and Visibility Graph Analysis (VGA): Strategies to evaluate visibility along movement pattern for safe space. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *385*, 012024. [CrossRef]
45. Hwang, J.H.; Lee, H. Parametric Model for Window Design Based on Prospect-Refuge Measurement in Residential Environment. *Sustainability* **2018**, *10*, 3888. [CrossRef]
46. Nubani, L.; Wineman, J. Using Isovists in Measuring Surveillance and Expected Guardianship in Residential Neighborhood Property Crimes. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 544. [CrossRef]

47. McElhinney, S. The Isovist_App: A basic user guide, v1.6. 2020. Available online: https://www.researchgate.net/publication/350107669_Isovist_App_UserGuide_v1-7 (accessed on 30 January 2024).
48. Housing our Ageing Population: Panel for Innovation. Available online: https://www.housinglin.org.uk/_assets/Resources/Housing/Support_materials/Other_reports_and_guidance/Happi_Final_Report.pdf (accessed on 30 January 2024).
49. Available online: https://www.atelierkempethill.com/0137-the-village (accessed on 30 January 2024).
50. Available online: https://www.jjw.dk/projekt/orestad-plejecenter/ (accessed on 30 January 2024).
51. Available online: https://pollardthomasedwards.co.uk/projects/index/new-ground-cohousing/ (accessed on 30 January 2024).
52. Available online: https://www.proctorandmatthews.com/project/chapter-house-lichfield (accessed on 30 January 2024).
53. Available online: http://www.wwmarchitects.co.uk/projects/almshouse-southwark (accessed on 30 January 2024).
54. Available online: https://www.archlro.de/en/projects/gemeindehaus-und-seniorenwohnungen-in-stuttgart#1 (accessed on 30 January 2024).
55. Available online: https://www.schwarz-architekten.com/project/wettbewerb-via-caguils-domatems/ (accessed on 30 January 2024).
56. Available online: https://bel.cx/projects/ (accessed on 30 January 2024).
57. Available online: https://regenerationstudio.weebly.com/seniorenresidenz-spirgarten.html (accessed on 30 January 2024).
58. Available online: https://www.subtilitas.site/post/74959359666/miller-maranta-retirement-home-zurich-2006 (accessed on 30 January 2024).
59. Available online: https://www.kvernaas.no/prosjekter/varden (accessed on 30 January 2024).
60. Available online: https://www.kruck-partner.de/referenzen/stadtcarre-bad-rappenau/ (accessed on 30 January 2024).
61. Available online: https://solinsieme.ch/index.php?page=Plaene (accessed on 30 January 2024).
62. Available online: https://issuu.com/radarcommunications/docs/offsite_mag_issue_20_web/12?e=15424601/6470417217 (accessed on 30 January 2024).
63. Available online: https://www.ad-houses.com/modular-homes-boost-retirement-living-developments (accessed on 30 January 2024).
64. Zajonc, R.B. Social Facilitation. *Science* **1965**, *149*, 269–274. [CrossRef] [PubMed]
65. Schneider-Skalska, G. *Kształtowanie zdrowego środowiska mieszkaniowego—Wybrane zagadnienia*; Wydawnictwo PK: Kraków, Poland, 2004.
66. Mikołajska, I.; Woźniak-Szpakiewicz, E. Population ageing as a challenge for architectural and urban design: Case study: Concept of Hybrid Senior Unit in Cracow (Poland). In *Virtual City and Territory. "Back to the Sense of the City: International Monograph Book"*; Centre de Política de Sòl i Valoracions: Barcelona, Spain, 2016; pp. 879–892.
67. Lozansky, E.; Rousseau, C. Combinatorics. In *Winning Solutions. Problem Books in Mathematics*; Springer: New York, NY, USA, 1996. [CrossRef]